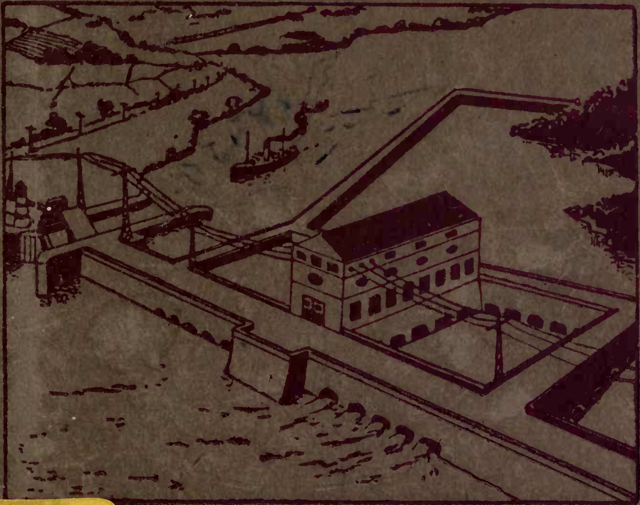
Tidal Power



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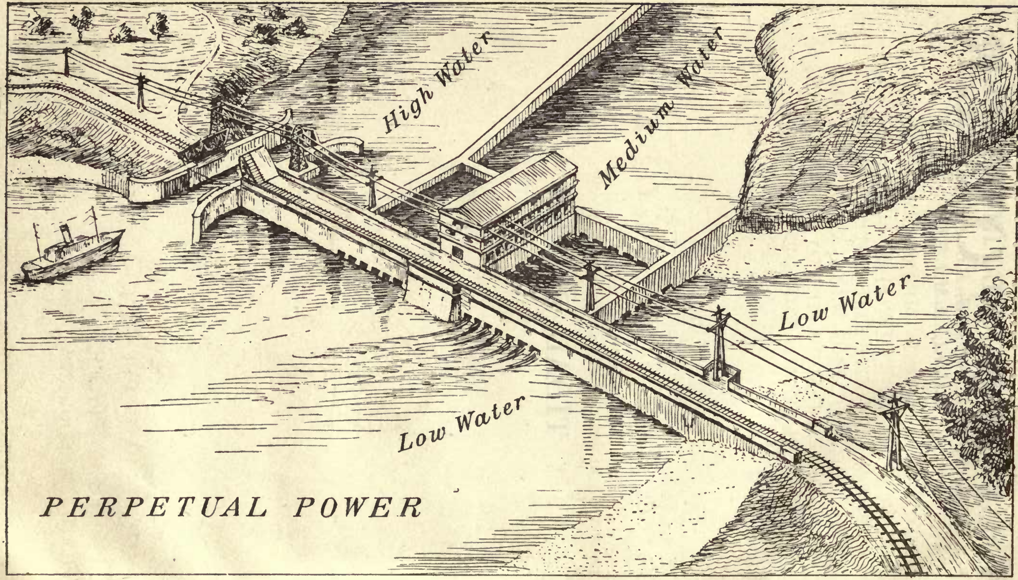
TIDAL POWER



AN EFFICIENT AND ECONOMICAL LAY-OUT FOR TIDAL POWER DEVELOPMENT

(*See also Figs.* 8-10)

Frontispiece

TIDAL POWER

TIDES AND THEIR MEASUREMENT; THE ESTIMATION OF POTENTIAL TIDAL POWER; COMPARISONS BETWEEN SYSTEMS OF DEVELOPMENT; THE FINANCIAL ASPECT OF THE PROBLEM; DIFFICULTIES TO BE OVERCOME; AND THE LINES FOR DEVELOPMENT

BY

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PREFACE

Ages ago, far back in the dim past, man must inevitably have " sensed " the enormous power embodied in the ceaseless, diurnal ebb and flow of great volumes of the sea into and out of every estuary, strait, or bay that came within his ken.

Gradually, as he became master of other forces in Nature, he is certain to have pondered on the possibility of enlisting this latent power into his service, as several centuries before the Christian era commenced we find records showing that he observed intelligently the action of the tides, and commented on their connection with the phases of the moon.

In the eighteenth and nineteenth centuries, such speculations took shape in " Tide Mills " run by water flowing from basins during falling tides, that had been filled by the previous rising tide.

Examples of such mills exist in England, on the Breton coast of France, in America and Spain, but, as far as can be ascertained, they were only of insignificant magnitude and

primitive design, and, in consequence of their intermittency, not suited to ordinary industrial uses.

Numberless proposals for the utilization of tides have, from time to time, been put forward, and large numbers of patents have been taken out. Many of these schemes are visionary and unworkable, and will not be considered here. Others showing considerable promise will be described.

The practical utilization of the tides for power purposes has only come within measurable distance in recent years, owing to our increased knowledge of the motion and magnitude of the tides, and of the laws affecting the flow of water; and owing to the great strides that have taken place in hydro-electrical power development, which have placed at our disposal the very efficient modern turbine and electric generator and plant for the conversion and transmission of electrical energy to considerable distances.

The existing very high cost of fuel, and the prospect that this cost is likely ever to increase, makes tidal power development a commercial possibility and attractive to capital.

With the ever diminishing supply of coal,

any possible means of conservation of this natural resource becomes of vital national importance, and should furnish an additional inducement for the use of tidal power.

An effort will be made in this small work to indicate some of the possibilities opened up by the use of tidal power; various difficulties to be confronted; likely systems of development; some financial aspects of the problem; and further research work that appears desirable.

The subject cannot exhaustively be dealt with in a work of this scope, which aims chiefly at stimulating interest in a field that is likely, in the near future, to attract a considerable amount of attention.

The solution of tidal power problems is a labour worthy of the best efforts of the engineer, whose *raison d'être* is "to direct the sources of power in Nature for the use of and convenience of Man."

A. M. A. STRUBEN.

BEACONSFIELD, BUCKS
September, 1920.

CONTENTS

CHAP.		PAGE
	PREFACE	v
	ILLUSTRATIONS	xi
I.	TIDES	1
II.	STANDARDS OF MEASUREMENT	14
III.	POTENTIAL TIDAL POWER	20
IV.	SYSTEMS OF TIDAL POWER DEVELOPMENT	36
V.	THE PREPARATION OF PROJECTS	72
VI.	FINANCIAL CONSIDERATIONS	84
VII.	RESEARCH	102
	INDEX	113

ILLUSTRATIONS

FIG.		PAGE
	An Efficient and Economical Lay-out for Tidal Power Development .	*Frontispiece*
1.	Illustrating the Formation of Tides . .	3
2.	Diagram showing Range of Tides at Devonport	9
3.	Intermittent Working. Single Basin. System A	42
4.	Intermittent Working. Single Basin. System B	45
5.	Intermittent Working. Single Basin. System C	48
6.	Continuous Working. Double Basin. System D	53
7.	Continuous Working. Double Basin. System E	56
8.	Continuous Working. Treble Basin. System F	60
9.	Plan of Power-house, showing Control of Water in Fore-bay and Tail-bay . .	62
10.	Diagrammatic Section of Power-house, Fore-bay, and Tail-bay	63
11.	Working Head and Power Output for Continuous Working Treble-basin System (F)	66
12.	Plan of Basins for Continuous Working, Treble-basin System (F) . . .	73

FIG. PAGE

12*a*. Chart for Rapid Determination of Contents of Basins 75

13. Section Through Proposed Barrage and Power House for Single Basin System. 79

TABLES

TABLE

I. Comparative Data on Basin Systems of Tidal Power Development 69

II. Comparative Costs for Steam-driven and Tidal-power Installations . . . 90

TIDAL POWER

CHAPTER I

TIDES

1. Knowledge Requisite. Some knowledge of the causes producing tides, their magnitude, and character, is desirable in considering problems for tidal development. It is proposed to give a brief treatment of this subject which should serve the purpose, while acting as a reminder to those who have already mastered the astronomical problems involved.

2. The Formation of Tides. Tides are produced by fluctuations in the resultant of the several forces of gravity and of centrifugal action which are felt at any given locality on the earth, caused by its rotation and by changes in the relative positions of the earth, moon, and sun.

The three principal motions to which cause these fluctuations are due are the following—

(*a*) The rotation of the earth about its axis, completed in one day.

(*b*) The revolution of the moon round the earth, completed in one month.

(*c*) The revolution of the earth and moon round the sun, completed in one year.

The changes in relative position to which these fluctuations are due are shown in Fig. 1.

The effect of these fluctuations at any given locality may be grasped by picturing an observer standing at this locality always facing north, with the earth carrying him in its rotation from his left towards his right hand ; that is, from west to east.

3. Spring Tides. Imagine such an observer in the northern hemisphere studying tidal conditions at new moon. Reference to Fig. 1 will show that during this phase of the moon its attraction is assisted by that of the sun, and that the following effects are produced—

At sunrise the observer will be standing on the earth where shown at *A*, and the sun and moon will lie on his right side in the east. In this position the several forces that act produce a resultant force which in effect is equivalent to a lateral pull, which causes "low water" near the observer and on the opposite side of the world.

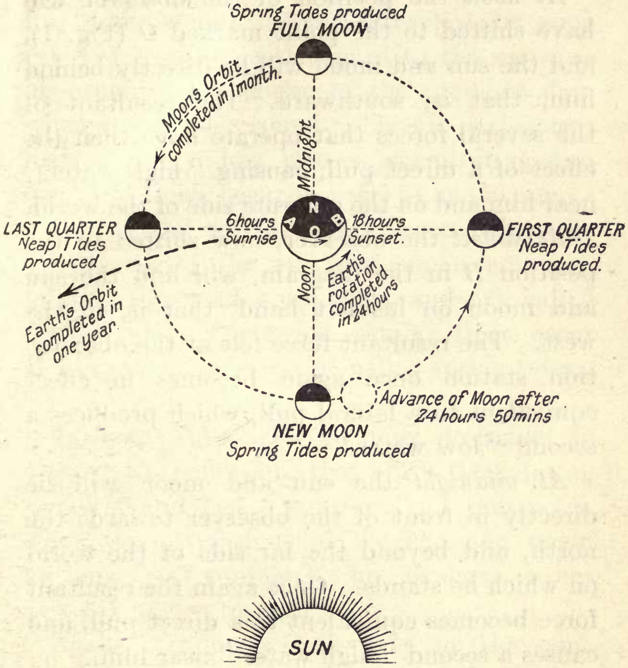

FIG. 1.—ILLUSTRATING THE FORMATION OF TIDES

Highest Spring Tides occur during Equinoxes with Moon in Perigee.

Lowest Neap Tides occur during Solstices with Moon in Apogee.

Ratio Sun's Attraction : Moon's Attraction = 1: 2·73.

At noon the position of the observer will have shifted to the point marked *O* (Fig. 1), and the sun and moon will lie directly behind him, that is, southward. The resultant of the several forces that operate have then the effect of a direct pull, causing " high water " near him and on the opposite side of the world.

At sunset the observer, now shifted to the position *B* in the diagram, will find the sun and moon on his left hand, that is, in the west. The resultant force felt at the observation station once again becomes in effect equivalent to a lateral pull, which produces a second " low water."

At midnight the sun and moon will lie directly in front of the observer towards the north, and beyond the far side of the world on which he stands. Once again the resultant force becomes equivalent to a direct pull, and causes a second " high water " near him.

The changes from high to low water and vice versa will be gradual, producing a quiet rise and fall, known as the " flow " and " ebb " of the tide.

Now, while the observer has been making his revolution with the rotation of the earth, the moon has been moving forward in its

orbit, and the observer will have travelled for 24 hr. 50 min. before he reaches the same relative position with regard to the moon as he occupied at sunrise of the previous day, when starting his round. Thus it is that two high and two low waters, constituting two complete tides, occur in each 24 hr. 50 min.

During the period of new moon, when the attractions of the sun and moon act conjointly, these tides are high, and are called *spring* tides. Somewhat similar tides occur at full moon, and are also called spring tides.

4. Neap Tides. It is now desirable to observe the conditions that affect tides during the first and last "quarters" of the moon, when the attractions of the sun and moon no longer act conjointly, but to some extent at right angles to each other.

Again, assume an observer in the same locality as before making a second observation with the moon in the "first quarter," that is, when it has travelled one-quarter of its orbit round the earth. Fig. 1 shows the following—

At sunrise the sun will be on the observer's right, that is, east; while the moon is directly

opposite him on the other side of the earth, in the north. In this position the sun and moon exercise attractions acting more or less at right angles to each other in approximately the ratio of 1 to 2·73. The moon's attraction being $2\frac{3}{4}$ times greater than the sun's, the resultant of the several forces that affect the observation locality produces "high-water" near the observer, but its height obviously will be *lower than* that of the high-water which occurs when the sun and moon act in conjunction as is the case at new moon, when spring tides occur.

At noon the sun will lie behind or to the south of the observer, and the moon to his right in the east. In this position the resultant of the several forces, of which the attraction of the moon is the greatest, will produce "low-water" near the observer; but in this case it will be *higher than* the level of the low-water produced during spring tides, as the depressing effect will not be so great.

At sunset, with the moon behind him and the sun on his left hand, a second "high water" will be produced.

At midnight, with the sun directly in front of him beyond the opposite side of the earth,

and the moon on his left hand, a second "low water" will be produced near the observer.

As before the observer must travel 50 min. (of time) beyond his original starting point before he catches up the moon, showing that thus again in every 24 hr. 50 min. two complete "high" and "low" waters will have occurred; in other words, two complete tides will have risen and fallen, or "flowed" and "ebbed."

During this second observation with the sun and moon exercising attractions more or less at right angles to one another relative to the earth, the tides rise and fall through a less height than during "spring" tides, and are called *neap* tides. Similar "neap" tides occur with the moon at "*Last Quarter.*"

5. The Range of Tides. The attraction of the sun on any given spot on the earth varies with its distance and position relative to the equator, and is obviously greatest when it is nearest to the earth and most directly over the locality under consideration.

The moon in its orbit round the earth similarly, but in a more powerful degree than

in the case of the sun, exerts an attraction which varies according to its distance and relative position, with reference to the locality considered.

These influences of the sun and moon affect the magnitude of the tides to a degree which depends on the extent to which they combine or oppose each other.

The *highest spring tides* occur during the *equinoxes* in March and September, at times when the moon is simultaneously in "perigee," that is, nearest the earth.

The *lowest neap tides* occur during the *solstices* in June and December, at times when the moon is simultaneously in "apogee," that is, farthest from the earth.

The difference in level between high and low water in any tide is called the *range* of the tide. As may be expected from inspection of Fig. 1, this range is greatest during spring and least during neap tides, gradually changing in magnitude from one to the other.

The range varies in different localities due to the configuration of the land; but, broadly speaking, the neap range is one-half of the spring range.

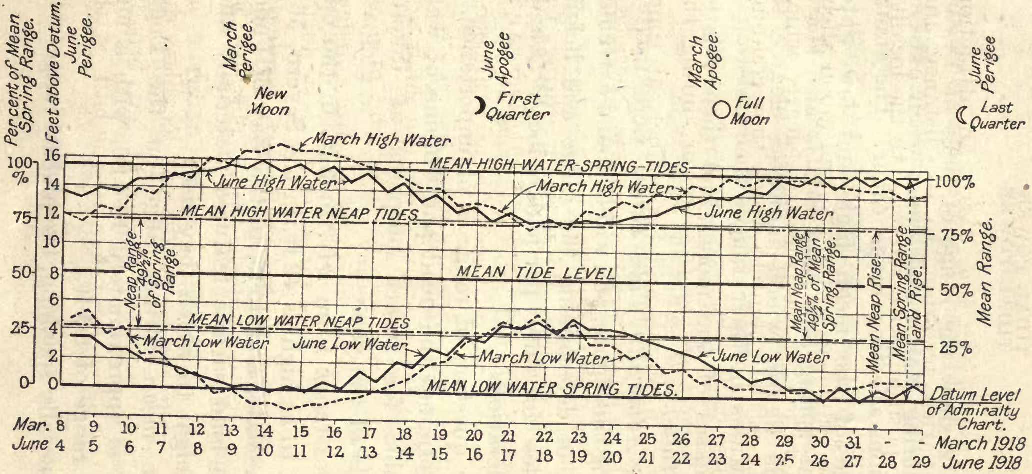

FIG. 2.—DIAGRAM SHOWING RANGE OF TIDES AT DEVONPORT

Fig. 2 show the range of tides at Devonport during March and June, when extreme conditions affecting range occur. The annual average of the mean high and low water level at spring and neap tide is also shown on this figure, which indicates clearly the fluctuations in their range, their relation to the phases of the moon, and their relative magnitude.

The *Admiralty Tide Tables* were used in plotting this figure, and will be found extremely useful in determining the range and heights of tides for any particular locality under consideration.

The question of range is of importance, as it determines the head and volume of water available for power purposes at different periods of the year.

Tides range from 2 ft. to 3 ft. in the open ocean to as high as 42 ft. in the Severn, 36 ft. at St. Malo, and 45 ft. in the Bay of Fundy, where land surface features materially affect the height to which they rise.

The mean spring range on the English coast is approximately 16·4 ft., with a mean neap range of 8·4 ft.

Generally speaking, the highest ranges occur

where tides enter funnel-shaped bays, estuaries, straits, etc., in which the open mouth faces the sea.

Wind and atmospheric pressure also cause disturbances in the range of tides, which, under certain conditions, may amount to as much as 6 ft. in localities where the physical conditions lend themselves to these influences.

The maximum possible fluctuations are important in considering the design and position of tidal works. These would obviously best be obtained from local observation; but, failing this, could be determined with a fair degree of accuracy from the Admiralty Tide Tables.

Mr. M. Gheury de Bray, in a pamphlet called "A Simple and Rapid Method of Tide Prediction," offers valuable information on this important subject.

6. The Establishment of Localities. The tides lag behind the moon in its passage over the meridian, and are affected by the retarding influence of land features. Thus a tide coming in from the open ocean is deflected or retarded by the configuration of the coast which it is approaching, and in consequence

progresses at different rates in different localities.

The time that elapses after the moon passes the meridian, before high water occurs at a given place on full and change days, is called the *establishment* of that locality.

In England this establishment varies for different ports from a few minutes to nearly twelve hours.

The actual establishment of any locality, failing direct observation, can be determined with fair accuracy from the Admiralty Tide Tables. Mr. Gheury de Bray's method of prediction should also prove of great assistance.

Charts showing *co-tidal lines* will be found useful in studying problems in which stations situated in various localities, and coupled to the same electrical distribution system, are concerned.

Such a chart represents the localities of "contemporary tides," and indicates the interval of time required for a tide to travel from one locality to another.

7. Height and Rise of Tide. The level of a tide above a fixed datum is called its *height*. The tide datum frequently used is the mean

low-water level of spring tides, and may conveniently, in England, be co-related to ordnance datum.

The maximum height above datum to which a tide rises is called its *rise.*

In Fig. 2, the rise of the tide is shown at daily intervals. Generally speaking, the neap rise is three-fourths of the spring rise.

The "height" of tide at any period intermediate between high and low water is best shown by tide-gauge diagrams. Failing these, the height may be determined by constructing a diagram on the lines laid down by Captain Tizard, R.N., in the Admiralty Tide Tables.

It will be found convenient to express these heights on such diagrams as a percentage of the total range as illustrated in Figs. 3 to 8. By means of such a diagram, the height of tide at any locality at any time between high and low water may be determined by multiplying the actual range at that locality by the percentage shown on the diagram.

CHAPTER II

STANDARDS OF MEASUREMENT

8. Units of Measurement Proposed. In tidal power development of any reasonable magnitude, large volumes of water will have to be handled, owing to the smallness of the head that will generally be available. For this reason, it is desirable to use large units of measurement, otherwise the figures employed become unwieldy.

It is suggested that the following units will be found convenient.

(i) LINEAR.—The *foot* should be used as the unit of measurement in stating dimensions of plant, structures, and the like.

(ii) SURFACE.—The *acre* will be found a convenient unit for stating the area of tidal basins, estuaries, and the like.

(iii) VOLUME.—The *acre-foot* is a good unit of volume for measuring the contents or capacity of tidal basins, and the volumes of water dealt with in estuaries, bays, etc., and the volume is equivalent to an acre of area covered by water to a depth of one foot.

(iv) Rate of Flow.—The rate of flow of water should be stated in cubic feet per second or in acre-feet per hour.

The *cusec*, which is a flow of water of 1 cub. ft. per second, has been found a conveniently sized unit in irrigation practice, and is the smallest that should be used.

The *acre-hour*, a term suggested for a rate of flow equal to 1 acre-foot per hour, will be found more convenient than the cusec in many cases for measuring the rates of discharge from tidal basins or in dealing with other tidal problems, as it is easily coupled to the other units of measurement suggested herein.

(v) Power.—The *horse-power* is a unit frequently met with in power problems, and should generally be regarded as the brake-horse power. Its value is work done at the rate of 33,000 ft.-lbs. per minute.

The *kilowatt* is the unit of power universally adopted in electrical practice, and equals 1,000 watts.

9. Symbols for Units of Measurement Proposed. Some of the more important units of

measurement and the symbols used to denote them in these pages are as follows—

Q = cusec = 1 cubic foot per second.
H = head of water in feet.
R = range of tide in feet.
D = diameter in feet.
A = area in square feet.
sq.ml. = square mile.
Ac. = acre.
Af. = acre-foot.
Ah. = acre-hour = rate of discharge in acre-feet per hour.
h.p. = horse-power.
kw. = kilowatt.
Unit = electrical units of energy = 1 kw.-hr.

10. Formulae Used in Computation of Power. The following formulae will be found useful—

1 Ac. = 1 acre.
= 43,560 sq. ft.
1 sq. ml. = 640 Ac.
1 Q. = 1 cu. ft. per sec. = 1 cusec.
= 3,600 cu. ft. per hr.
= 86,400 cu. ft. per 24 hr.
= 1·9835 acre-feet per 24 hr.
1 Af. = 43,560 cu. ft.

1 Ah. = 1 acre-foot per hour.
= 43,560 cu. ft. per hour.
= 24 acre-feet per 24 hr.
= 12·1 cusecs.
= 1·025 kw., if flow is under 1 ft. head.
= 1 kw. under 1 ft. head at 98% efficiency.
= 1 h.p. under 1 ft. head at 73% efficiency.

1 h.p. = 0·746 kw.
= $0 \cdot 1134 \times Q \times H$.
= 1 cusec under 8·82 ft. head.
= 8·82 cusecs under 1 ft. head.
= 0·73 acre-hour under 1 ft. head.
= 1 acre-hour under 1 ft. head at 73% efficiency.

1 kw. = 1·34 h.p.
= $0 \cdot 0847 \times Q \times H$.
= 1 cusec under 11·81 ft. head.
= 11·81 cusecs under 1 ft. head.
= Ah. × H nearly.
= 1 acre-hour under 1 ft. head at 98% efficiency.

Kilowatt-hours = Af. × H (nearly).

The use of these formulae is a matter of simple arithmetic and will rapidly give results sufficiently accurate for practical purposes.

The method of use is fairly obvious, but to avoid any misunderstanding an example is given which will serve to show what is necessary.

EXAMPLE.—Assume that it is desired to ascertain the power that would be developed from a basin 3 sq. ml. in area from which water is being drawn off through turbines under a head of 12 ft., while the water level is dropping 2 ft. per hr.

Surface area	=	(3 sq. ml. × 640) Ac.
	=	1920 Ac.
Rate of Flow	=	1920 Ac. × 2 ft. per hr.
	=	3,840 Ah.
Power in Kw	=	Ah. × H (nearly)
	=	3,840 × 12
	=	46,080 kw.

Let the efficiencies of the plant be as follows—

Turbines, 80 per cent.

Dynamos, 94 per cent.

Transformers and transmission line, 85 per cent.

Then the over-all efficiency is—

$$0{\cdot}80 \times 0{\cdot}94 \times 0{\cdot}85 = 0{\cdot}6392$$

or, say, 64 per cent.

The power delivered will therefore be 64 per cent. of 46,080 = 29,400 kw., or, say, 29,000 kw.

If this rate of power output is maintained for nearly 3 hrs. during each rise and fall of the tide the total running time per day will be, say, 12 hrs.

Under these conditions the energy generated will be—

29,000 kw. × 12 hr. = 348,000 kw.-hr. per day.

11. Corrections for Efficiency. In practice, the theoretical values obtained by the use of formulae often need correction for various

losses, and it is important to take these into account. In many cases the losses are expressed in terms of the "efficiency" of the plant or apparatus ascertained by actual tests. In other cases, the correction for losses should be made from the result of experience, or from computation of loss to be expected in view of experience gained under parallel conditions.

In some formulae the corrections for efficiency or other losses are taken into account in the equations employed.

CHAPTER III

POTENTIAL TIDAL POWER

12. Theoretical Latent Power of Tides. The latent power theoretically available from tides can only be described as of vast magnitude. Interesting calculations could be made of the amount of power which might be derived from this source, but the figures obtained would be of academic interest rather than of real practical value, hence they will not be discussed at length here.

To convey some idea of the amount of power available in theory, it should be borne in mind that with a range of 10 ft. each square mile of tidal water that is utilized, is capable, at full efficiency, of producing approximately 11,000 kw., running for 3 hrs. on each rise and fall of the tide, thus giving a total of nearly 12 hrs. run per day, with an output of 130,000 kw.-hr. per 24 hrs.

In practice, it is neither possible to obtain full theoretical power, nor is it within man's power to control vast oceans. The best we can hope to achieve is the utilization of a

small fraction of the tidal power that is available near the coast, where suitable natural facilities exist for impounding portions of the sea, and for constructing power installations.

13. Potential Power : Practicable. At the present time, developments for the utilization of tidal power are practically limited to localities where good natural facilities exist for building tidal basins, where portions of the tidal flow can be impounded and controlled, and where conditions are suitable for the erection of power stations, on the lines of modern hydro-electric stations.

Such facilities are most likely to be found in estuaries, bays, and straits, where the tides have sufficient range to give the necessary head for operating turbines at a reasonable cost.

Assuming vertical-sided reservoirs or basins, it should be possible with a range of 10 ft. to produce per sq. ml. 30,000 kw.-hr. per day, working constantly, or 50,000 kw.-hr. per day working intermittently, assuming 100 per cent. efficiency in both cases. In practice, it will not be feasible to form tidal basins with vertical sides throughout, neither is it possible to work at 100 per cent. efficiency. Under

favourable conditions, it should be possible to obtain 50 per cent. of the theoretical power available, if due allowance is made for the sloping sides of containing basins, and for the usual losses in turbines, generators, etc. On this basis, and assuming a tidal range of 10 ft., *each square mile of tidal basin should yield*—

(*A*) With *intermittent* working, 2,500 kw. running 10 hr. per day, producing 25,000 kw.-hr. per 24 hr.

(*B*) With *constant* working (each acre of tidal basin contributing roughly 1 kw.) approximately 640 kw., with an output of 15,000 kw.-hr. per day.

The power output depends directly upon the volume of water passed through the turbines, multiplied by the head under which they operate.

As the volume and head vary directly with the range for a given area, it follows that *the power available varies with the square of the range* (i.e., Power $\propto R^2$). Thus, a 20-ft. spring range will produce four times as much power as a 10-ft. neap range, on equal reservoir areas. This large fluctuation in range is one of the chief objections to the use of tidal power, as it complicates the problem of the

consumption of the power produced, and introduces the difficulty of operating turbines under considerable variations of head.

14. Examples of Potential Power. Modern turbines can operate under heads as low as 3 ft. In many localities, tidal ranges of 10 ft. and over exist, while in other localities far higher ranges will be met with. In the Severn, for example, with a spring rise of 42 ft., it should be possible to operate on a range of approximately 30 ft., producing nine times more power than would be produced with a range of 10 ft. In such a locality, with tidal basins, aggregating 20 sq. ml. in area, over 100,000 kw. could be installed, capable of producing 2,500,000 units per day running constantly, or 4,500,000 units per day, running intermittently (*see* § 17).

On the French coast, it should be possible to operate plant, under a range of 25 ft., which would make possible an output of from 90,000 to 150,000 units per day per sq. ml.

In the Bay of Fundy, where the spring range reaches 45 ft., it should be possible to operate plants under a range of from 30 to 32 ft. In this locality, basins aggregating 14 sq. ml.

in extent, would enable over 80,000 kw. to be installed, producing 1,500,000 units per day working continuously, or 3,000,000 units per day working intermittently.

These examples indicate the enormous possibilities that exist for tidal power development. The figures given, not being based on actual surveys, should be regarded merely as indicating on broad lines what may be achieved in actual practice.

15. Tidal Power Developments under Consideration. In France, serious consideration has been given to possible developments of tidal power on the Seine and on portions of the north-west coast.

In Canada, at Hopewell, New Brunswick, a scheme for the development of 90,000 h.p. capable of being extended to 200,000 h.p. is at present contemplated. This scheme is considered to be quite feasible from the engineering point of view, and attractive from the commercial standpoint. It should be possible, by adopting a more favourable system of operation than the one proposed, very considerably to increase the output of power.

England is beginning to awaken to the importance of utilizing tidal and hydro-electric power, and may soon be forced, by the increasing cost of coal, to take active steps. *With the high ranges of the tides met with on many parts of the English coast, the prospects of tidal power development are distinctly promising.*

16. Difficulties to be Encountered in Tidal Power Developments. One of the chief difficulties that confront tidal power development schemes will be the considerable fluctuations in the "range" between spring and neap tides, which signify great variations both in head and power output. It may be possible to overcome the difficulty by pumping water into reservoirs above tide level, by means of surplus power available during spring tides, and utilizing the water thus stored for making up the deficiencies of power during neap tides. Considerable losses are inevitable in this process and, broadly speaking, only about 50 per cent. of the surplus energy so employed could be recovered.

Another difficulty to be encountered is the fact that turbines can only operate within

limited variations of head, which, under present practice, cannot exceed 50 per cent. on either side of the mean head. This difficulty is likely to be reduced by further improvements in turbine design.

A further difficulty that will be met with in tidal power development is that due to proprietary or long-established rights. The only way that this difficulty is likely to be dealt with satisfactorily is by means of legislation giving wide powers to some properly constituted authority.

This may be done by extending the powers to be conferred on the Commissioners under the Electricity (Supply) Act, 1919.

17. Fields for the Use of Tidal Power. (*A*) *Intermittent Systems.* Intermittent systems would provide the greatest output of the power available from tides, but are objectionable owing to their intermittency, as normally the plants would only operate for about 3 hrs. at a time during four periods per day (" tide-day " of 24 hr. 50 min.), the time of starting and stopping becoming 50 min. later each day. Such intermittent systems would be feasible if power could be utilized directly

it was generated. This would be possible if the power produced were fed into a "distribution system," which also took current from steam or hydro-electric stations, serving industrial centres which were capable of taking a large night load.

An invaluable outlet for intermittent tidal power would be provided by electro-chemical industries capable of using such power as and when available. It seems within the range of possibility that such industries might, with advantage, be established in conjunction with tidal power developments.

(*B*) *Constant Systems*. In many localities where coal is expensive and transport facilities are bad, tidal power schemes capable of operating continuously should rival other forms of power. With good natural facilities, it should be possible to obtain 60 per cent. of the output that would be available if intermittent working were adopted.

By operating the turbines at 71 per cent. of the mean spring range, the output is double that obtained on the neap range, while the power available during spring tides is double that obtained by operating at 71 per cent. of the mean spring range and four times that

obtained from the neap range. If this surplus is used for pumping into reservoirs, and only half is recovered, owing to conversion losses, then by utilizing the water stored to make up deficiencies during neap tides, it should be possible practically to double the power that would otherwise be produced if the plant is designed to run on the neap range only.

Tidal power developments stand a reasonable prospect of being commercially successful where the output of power that could be used as a commencement is sufficient to pay for the first cost of the necessary works to form tidal basins, and a small portion of the power plant that would ultimately be installed. This is due to the fact that the turbines and generators actually installed could be made to suit the initial requirements, further units being added from time to time in the future as required, provided always that the tidal basins are correctly designed and constructed, in the first instance, to make such additions possible.

18. The Magnitude of the Field for Power. The field in which tidal power could compete is enormous, as the present use of power—

especially electric power — is large and constantly increasing.

To convey some idea of the magnitude of this field, an estimate by Sir Dugald Clerk * may be quoted, which gives the world's power consumption as follows—

POWER USED IN:	
Factories, including lighting and street railways:	
United Kingdom. . . .	13,000,000 h.p.
United States	29,000,000 h.p.
British Dominions . . .	6,000,000 h.p.
Other Countries	27,000,000 h.p.
	75,000,000 h.p.
Railways	21,000,000 h.p.
Shipping	24,000,000 h.p.
Total.	120,000,000 h.p.

Hydro-electric power already plays an important part in this vast field, and has been developed chiefly in the United States, Canada, Switzerland, and Scandinavia.

As an indication of the size and scope of the field for water-power, figures prepared by the Canadian Bureau of Statistics, Department of Trade and Commerce co-operating with the Dominion Water Power Board of

* Given in a pamphlet on "Power in Alberta," published by the Commission of Conservation of Canada.

the Department of the Interior, are of interest, and show that there is in Canada—

Turbine or water-wheel power installed	2,418,000 h.p.
,, regularly employed . . .	2,215,000 h.p.
Power installed per 1,000 of population	274 h.p.

The principal uses to which this power are devoted are as follows—

	Horse-power.
Pulp and paper industry	473,265
Lighting purposes	434,613
Mining industry	177,728
Flour and grist mills	42,736
Lumber and saw mills	37,913
Other manufacturing industries. . .	172,956

Since the above was written the third Interim Report of the Water Power Resources Committee of the Board of Trade has been issued, dated 1st December, 1920. As this Report gives the considered views of an authoritative body, it is worthy of careful consideration, and should carry great weight. Sections 17 to 25 of the Report bear closely on subjects dealt with by the author, and, as they express the independent views of a body with whom he has not had the honour of coming in contact, they are given *in extenso* for the benefit of the reader—

THE TIDAL POWER PROBLEM

(17) We do not propose in this Report to survey in detail the general subject of tidal power, but we think it desirable to indicate in broad outline the nature of the problem.

(18) The tidal movement of the waters around our coasts represents a colossal expenditure of energy, but this energy is not immediately available, and its value to the inhabitants of the British Isles is dependent upon the possibility, or otherwise, of devising means which will render it available for ordinary industrial purposes at an economic price.

(19) The energy *directly* available is intermittent and variable.

During any one tide the water is practically still for a considerable time at the periods of high and low tide; it rises or falls with maximum speed about the middle of the tidal range; and the rise and the fall of the tide may take different times. The effect of these variations is to cause the rate of output of energy by the water to vary from zero at high and low tide to a maximum reached about mid-tide. Again, from day to day, the time of high water alters, and there are lunar cyclical variations in the amplitude of the tides. The output of energy during a Spring tide is thus several times that during a Neap tide. Irregularities, such as occur in the underwater configuration of almost every large natural tidal basin, give rise to additional variations in the power output.

If an electro-chemical, electro-thermal, or other process were devised capable of absorbing an intermittent power supply subject to variations of this character, the commercial value of tidal power would be greatly increased; for since normal industrial operations cannot accommodate themselves to such variations, it is necessary to provide means for converting the output into a continuous supply more or less constant throughout the working period, in spite of the variations caused by Spring and Neap tides. This conversion can be accomplished only at the expense of overall efficiency.

20. Neglecting for the moment proposals to generate small amounts of power by current motors and other means, which clearly are capable of utilizing only an

insignificant fraction of the total power available, it would seem that the only practicable method of generating power from the tides involve the provision of one or more dams or barrages for impounding the water in tidal reservoirs, and the use of the water to drive turbines.

Various schemes have been proposed for obtaining a continuous supply of energy by the co-ordinated operation of several tidal reservoirs formed by a number of barrages. It has also been proposed to generate power at two different sites between the tidal cycles of which there is a difference of phase and to utilize the power produced at one installation to bridge the non-productive periods of the other. Mr. J. O. Boving has directed our attention to the possibility of thus utilizing in combination tidal power schemes on the Severn and the Dee. Without entering upon a detailed discussion of the merits and drawbacks of multiple reservoir schemes, we desire to point out that, although such schemes secure continuity of supply, they do not in themselves eliminate the serious difficulties caused by the difference between the outputs of Spring tides and Neap tides.

When a single barrage is employed, it is necessary to provide auxiliary means for storing a portion of the energy during the periods of maximum output, and for this purpose, the most promising method involves the use of a supplementary high-level reservoir into which water is pumped which is afterwards used in secondary turbines to develop energy as required. Alternatively, the tidal power scheme might be used in conjunction with one or several steam-power stations.

It also seems possible that other means might be devised for storing the energy generated. We have, however, laid less stress on the search for new methods which may theoretically be possible than on the fuller investigation of methods which are already recognized as valid.

The precise details of the method to be adopted in any particular case will necessarily be dependent upon the natural characteristics of the tidal basin under consideration. Certain broad deductions can be drawn from a theoretical consideration of assumed conditions, but it is essential from the outset to take cognizance of practical limitations and opportunities in order to arrive at a reliable decision on any particular scheme

Civil Engineering Aspects

(21) Evidently, since a barrage must be erected, the character of the foundations and the depth and nature of the channel are features of prime importance ; but, broadly speaking, if the conditions are favourable, the erection of a dam does not present any serious difficulty. Nevertheless, a considerable amount of preliminary investigation may be required to determine the best situation for the dam, and a study of the topography and geological characteristics of the district will be necessary in order to disclose the best site for a supplementary reservoir, if, as is almost certain to be the case, storage is necessary.

A hydrographical survey of the bed of the estuary would also have to be undertaken, as accurate knowledge of the quantity of water available between different levels is essential.

(22) The erection in a tidal way of an obstruction such as the projected barrage would evidently effect considerable modifications in the already prevailing currents ; powerful reaction currents might be set up, and it is to be anticipated that the normal scouring action would be modified, and the bed and possibly the banks of the estuary correspondingly affected. The deposition of silt carried into the estuary by the rivers flowing into it would probably also be modified. These matters, of considerable importance in connection with navigation, need experimental examination.

The height reached by the water in the tidal basin would depend largely on the cycle of operation of the turbines, but at any particular spot it would be influenced also by the shape of the basin. If the turbines were worked on a falling tide only, the water level would never sink below a predetermined level, fixed probably at about half tide, and the effect would be to create a large dock, which would facilitate navigation.

Mechanical, Electrical, and Hydraulic Aspects

(23) The mechanical, electrical, and hydraulic aspects of the tidal power problem and their co-ordination present conditions which are unprecedented, and in regard to which there is little practical experience to serve as a guide.

Thus, the maximum or peak output of the tides occurs

during a few hours only of every fortnight, and it is necessary to decide to what extent provision should be made for the absorption and storage of the energy available only at these times. If all the energy is to be developed, some turbines will have to be installed which for a very considerable proportion of the lunar cycle will be idle ; if less machinery is installed, its load factor will be greater, but a portion of the power will be lost. The determination of the economic limit beyond which it will not pay to install machinery and provide storage is one of the most complex difficulties of the problem, for it is intimately bound up with the details of the design of the machinery and the entire lay-out of the plant.

(24) As regards the hydraulic side of the question, all the difficulties of working under low heads are presented in an aggravated form. The maximum amplitude of Spring tides in the Severn Estuary, where they are exceptionally high, is of the order of 40–50 ft., whilst the range of Neap tides is considerably less. The working head giving maximum output over a given tide depends on the tidal range, and, to a smaller degree, on the variation in the area of the water surface at different stages of the tide. Thus, to obtain the maximum output from all the tides in a lunar cycle, it would be necessary to work the turbines under heads which alter the variations in the tidal amplitude. For example, with a tidal reservoir having vertical sides, and operating with a constant head during any one tide, theoretically, the optimum result would be secured by working the turbines under a head equal to half the tidal range. In the case of the Severn, where the Spring and Neap tides of one lunar cycle may be 42 ft. and 16 ft. respectively, a variation of head between 21 ft. and 8 ft. would be involved. Again, during any one tide, the natural rate of inflow and outflow vary in such a manner that it becomes necessary to deal either with a varying head or with great variations in the quantity of water passing through the turbines, or with both.

In a single barrage scheme, the turbines may be worked on the falling tide only, or on both the ebb and flow of the tide. A decision in regard to this matter will involve considerable modification in the form of the inlet and discharge passage ways of the turbines and the method of operating and controlling them.

It would appear that, under present manufacturing conditions, the maximum output of a single turbine unit under a head of 4 metres is about 2,500 brake horse-power, so that it is clear that a considerable number of turbines would be required to absorb the available power in the Severn Estuary and the problem of regulation assumes serious proportions.

The difficulties in the way of the designer confronted with the task of producing a turbine to meet such conditions and still maintain a reasonable efficiency and possibly constant speed are apparent.

(25) Probably it will be thought necessary to drive electric generators by means of the turbines. Considerable progress has recently been effected in increasing the specific speed of low-head turbines, but with the highest speeds yet attained, if the generator is to be coupled direct to the turbine, the electrical unit will be very costly. Gearing has been suggested for speeding-up and thus reducing the size and cost of the electric generator, but the production of gears for transmitting heavy loads at high efficiency is necessarily an expensive process, and there is little actual experience of the use of slow-speed prime movers with geared-up generators. The possibilities in this direction need to be carefully explored.

The choice as between alternating current and direct current will be dependent upon a number of considerations. In the case of alternating current, the general convenience of three-phase working needs to be carefully weighed against the difficulties which will follow on possible variations of speed and therefore frequency; as regards direct current, the possibility of operating without undue inconvenience under reasonable speed variations has to be balanced against the high cost of transforming and difficulties in the way of using high voltages when this type of current is used. A question of importance in deciding between alternating current and direct current is whether any portion of the electricity generated is to be supplied directly to the consumer or whether the whole is first to be converted into the potential energy of water in a high-level reservoir and then re-converted into electrical energy by high-head turbines driving secondary generators.

CHAPTER IV

SYSTEMS OF

TIDAL POWER DEVELOPMENT

19. Suggested Methods for Utilizing Tides. Many suggestions for the development of tidal power have been made from time to time, and large numbers of ideas have actually been patented. Some of the systems proposed are based on the idea of compressing air for subsequent use, but these are likely to involve expenditure out of all proportion to the benefits likely to be achieved.

Other systems proposed depend for their motive power on weights actuated by the tide during its rise and fall, or on floats or paddle-wheels actuated by the current produced during the run of the tide. Obviously such systems would present great difficulties in operation, and they cannot be regarded as feasible solutions of the problem.

Power development by such systems is not considered as in any way providing adequate means for the utilization of tides on the scale

that would be required to meet the developments which may be anticipated in the future.

Various systems have been suggested for utilizing the tides flowing into and out of basins or reservoirs for operating turbines or waterwheels, and, to a very limited extent —as in the case of small tide-mills—they have actually been put into operation. The production of power on these lines appears to offer the best solution of the problem thus far advanced and, being practical, will be discussed at greater length here.

20. Reservoir or Basin Systems. The principle underlying all tidal power turbine-driven systems consists in the formation of one or more basins or reservoirs, which are replenished by the tide from time to time, thus furnishing a supply of water at a suitable head to develop power.

In some systems, power is developed only when the basin or basins are being emptied, whilst other systems utilize the tide both during the filling and emptying of the basins.

In all basin systems, suitable natural facilities for the construction of dams or retaining walls will be essential where economy is

necessary. Such natural facilities will most frequently be found in straits, bays, estuaries, lagoons, or natural depressions.

21. Classification of Basin Systems. Basin systems can broadly be classified into—

(I) Intermittent systems,
(II) Continuous systems.

As tidal power development is only at present in its initial stage, it is possible that other systems may be formulated in the future, which cannot even be foreshadowed at the present moment.

In a work of this character, it is not possible to discuss fully the many rival systems that have been put forward, and therefore the chief features of the most promising systems only will be considered.

22. Basis of Comparison of Basin Systems. With a view to presenting the subject in the simplest possible manner, three intermittent and three continuous power systems will be describee.

So as to simplify a comparison between these systems, an endeavour has been made

to place them on the same basis as far as possible. In each case, the range is assumed to be 10 ft., the rate of discharge during operation of the plant is considered to be constant; whilst the basins are regarded as of constant area, that is, as having vertical sides. Plants are regarded as producing power at full theoretic values, that is, at 100 per cent. efficiency—as actual efficiencies depend on the design of installed plant, which may vary with differing conditions, and as a uniform basis is desirable. The various diagrams (Figs. 3 to 8) accompanying the description of each system are drawn to the same scale and on similar general lines. This will enable the rival systems, at least in so far as theory is concerned, to be compared on a fair footing on what may be termed "ideal" conditions.

In practice, the actual result obtained will be modified by local conditions and by various factors which must be taken into consideration for each individual locality on its own merits, and the necessary correction will have to be made to determine the real position from actual rates of flow and efficiency of plant used.

In the figures illustrating these systems, the upper diagram shows the relative water levels

from which the head on turbines can be obtained, whilst the lower diagrams show the direction of flow of the water into and from the basins and through the turbines. These illustrations are only diagrammatic and do not necessarily represent the arrangement of sluices, turbines, and basins which would be adopted in practice. The question of the working arrangement necessary in practice is discussed in Chapter V.

(I).—Intermittent Systems

23. Single Basin : System (A). The fundamental principle on which all basin systems are founded is shown in its simplest form in Fig. 3, which illustrates System (A). In this system one basin is used, which is fitted with sluice gates and turbines as shown diagrammatically in the Key Plan. In operation, this basin is filled by the rising tide, the water being impounded by closing the sluice gates at high water, when the tide begins to turn. When the tide has dropped sufficiently to give the necessary working head, the sluice gates are opened and the water contained in the tidal basin generates power by being run through turbines back to the sea, until the

tide turns at low water. The succeeding rising tide ultimately refills the basin, which is then ready for a repetition of the cycle of operations. This system is the simplest that can be devised, and is the one that has been employed in operating small tide mills which have been installed at various localities as previously mentioned.

The successive stages in the working may briefly be described as follows—

Stage 1. Sluice gates shut at high tide, the water being retained in tidal basin, whilst tide falls.

Stage 2. The basin empties through turbines to the sea, whilst the tide simultaneously continues falling until low water is reached.

Stage 3. Tide rising, sluice gates shut.

Stage 4. Sluice gates opened, tidal basin filling with tide rising.

The maximum power available under this system per 100 acres, with a range of 10 ft., would at 100 per cent. efficiency be approximately 920 kw. running for 25 per cent. of each tide equal to 3·1 hrs., producing during two tides 5,500 kw.-hr. per day of 24 hr. This is 50 per cent. of the theoretical energy

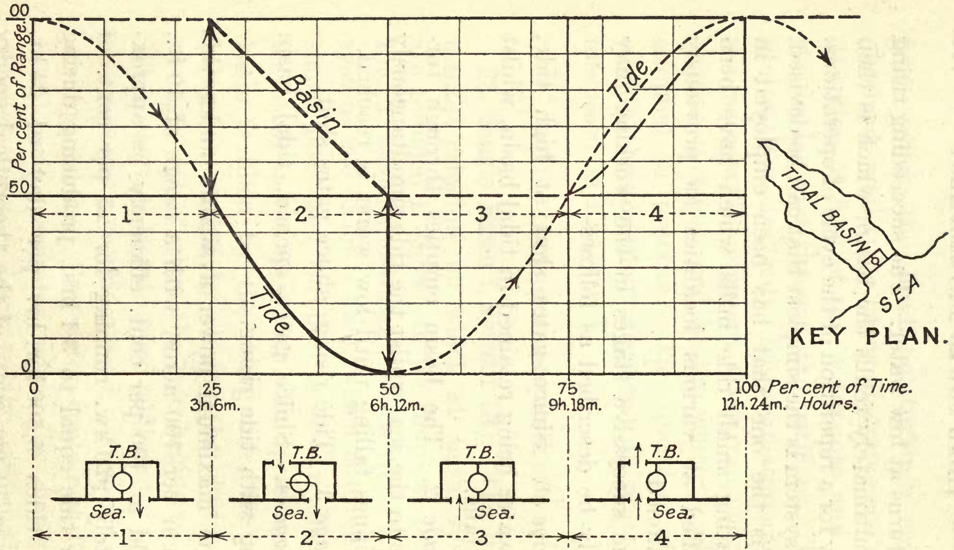

FIG. 3.—INTERMITTENT WORKING. SINGLE BASIN
(*System A*)

available if the tide were used when both rising and falling.

The maximum amount of energy is produced when the working head approximates to 50 per cent. of the range, and the plant runs from half-tide to low water.

The disadvantage of this system is that only two running periods, of 3·1 hr. each, are obtained per 24 hr. 50 min., and that the power of the rising tide is not utilized.

The intermittency of the system renders it unsuitable except in cases where extreme simplicity is desired,* and where power can be used as and when produced, either day or night.

24. Single Basin : System (B). This system, as illustrated in Fig. 4, is a development of System (A), in which the tide is utilized while rising as well as when falling, and gives the nearest approach to the maximum theoretical potential power, which would be obtained if turbines were run from half-tide to high and low water respectively, under a head approximating 50 per cent. of the range,

* Or where the natural facilities do not lend themselves to the use of more efficient systems.

assuming that the basin would be instantaneously flushed out at low tide and filled up at high tide. Theoretically this would provide double the amount of power produced under Scheme (A). In practice, instantaneous flushing is impossible, and owing to the time required to empty and fill the basin at low and high water respectively, it cannot be entirely emptied and filled, nor run for a complete half tide, and therefore cannot develop the full amount of latent power possible in theory.

The cycle of working in this system is shown by reference to Fig. 4 to be as follows—

Stage 1. The basin is filled as rapidly as possible when the tide nearly reaches high water, and until the water levels of the basin and the sea coincide. The gates are then closed, while the tide drops.

Stage 2. When the requisite head is reached, the sluices are opened and the turbines run, discharging back to the sea till near low water.

Stage 3. The water remaining in the basin, is flushed out as rapidly as possible into the sea until its level coincides with that of the

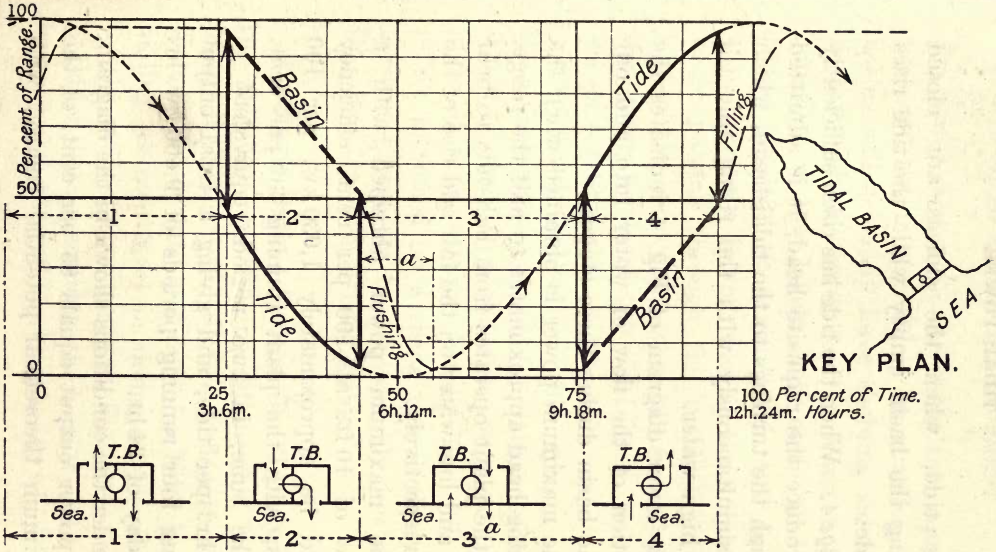

FIG. 4.—INTERMITTENT WORKING. SINGLE BASIN
(*System B*)

rising tide, when the sluices are closed keeping the basin empty while the tide rises outside.

Stage 4. When the tide has risen sufficiently to produce the requisite head, it is admitted through the turbines to the tidal-basin, which fills simultaneously with the rising tide till near high water.

The lower diagram of Fig. 4 indicates the direction of the flow of water into and out of the basin during these stages.

The maximum power is obtained when the working head approximates to half the range, and the plant operates from half-tide to near high and low water on the fall and rise of the tide respectively.

The maximum power obtained with a range of 10 ft. at 100 per cent. efficiency would be approximately 1,030 kw. per 100 acres, with the plant running 36 per cent. of the time, in two periods equivalent to 4·71 hr. per tide, and giving a total output during four running periods of 9,400 kw.-hr. per day of 24 hr.

Under the conditions shown in the diagram, the power output equals 85 per cent. of the maximum theoretical potential energy, with

the power output on the rising tide equal to that on the falling tide. In practice, tidal basins will generally have shelving sides and bottom, which, owing to the lesser holding capacity at low levels, will mean that the power obtained on a rising tide will be less than that on a falling tide, as the volume of water passing through the turbines will be less in this case than when discharged from the upper levels of the tidal basin into the sea on a falling tide.

The disadvantages of this system are: (i) its intermittency; (ii) the dangerous scour which is likely to occur with the rapid flushing and filling of the basin; and (iii) the power produced on a rising tide is likely, in most instances, to be considerably less than that developed on a falling tide.

25. Single Basin: System (C). This system is a modification of the conditions that would obtain if the tide were allowed to flow through turbines freely into and out of a tidal basin, finding its own level in doing so, as shown by the chain-dotted curve in Fig. 5.

Under these conditions, the head would vary from zero to the full working head, which the

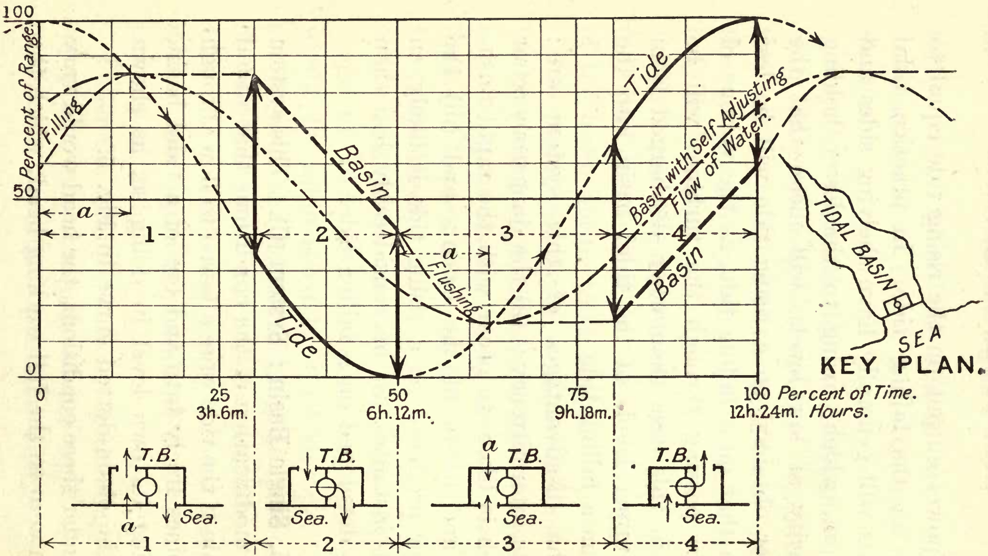

FIG. 5.—INTERMITTENT WORKING. SINGLE BASIN
(*System C*)

free flow of water into and out of the basin would cause.

In practice, such great variations in head are not permissible and free flow is, therefore, not allowed, the water levels of the basins being controlled to give the necessary working head.

The cycle of working under this system may briefly be described as follows—

Stage 1. The basin is filled as rapidly as possible without creating undue scour, till the water levels in the basin and tide coincide, when the sluice gates are shut, retaining the water impounded whilst the tide falls.

Stage 2. When the requisite head is reached, the sluice gates are opened and the turbines operate with water discharging to the sea until low water occurs.

Stage 3. The balance of water contained in the basin is flushed out as rapidly as possible, without creating undue scour, till its level coincides with that of the rising tide. The sluices are then shut to exclude the sea, while the tide continues to rise.

Stage 4. When the requisite head is reached, the sluices are opened and the turbines put into operation, running till high water occurs.

The lower diagrams (Fig 5) indicate the directions of flow of the water throughout the cycle.

Under the conditions shown in the figure, the maximum power is produced when the head approximates 50 per cent. of the range. On a 10 ft. range, at 100 per cent. efficiency, the maximum power is approximately 900 kw. per 100 acres, running 40 per cent. of the time, during two periods totalling nearly 5 hr. per tide. This will give a total output of 8,600 kw.-hr. per day, which is equivalent to 78 per cent. of the maximum theoretical potential energy.

In the system shown, the power on rising and falling tides would be equal, with vertical-sided reservoirs. In practice, the reduction in holding capacity at the lower levels of the basin, as already explained in connection with System (B), would normally mean the production of less power on a rising than on a falling tide, although the disproportion should be considerably less than under System (B), as the bottom levels of the basin are not used in this instance as they are in System (B).

The flushing and filling in System (C) are far less violent than in System (B), when

both are working at maximum capacity, whilst the running time is longer. For these reasons, System (C) is considered to be the best intermittent system that has, up to the present, been proposed.

In each of the three intermittent systems shown, the rate of discharge is considered as constant, and the water is considered as all passing through the turbines. In practice, the rate of discharge may be varied within the limits of divergence of head permissible on the turbines, and only a portion of the tide may be required to pass through the turbines.

Provision will therefore be required for the direct flow of water between the basin and the sea besides that passing through the turbines, and for controlling the direction and volume of the flow indicated diagrammatically in Figs. 3 to 5. Suggestions as to how this may be arranged will be offered in Chapter V on "The Preparation of Projects."

II.—Continuous Power Systems

26. Double Basin : System (D). For continuous working, two or more basins are required to cover the dead periods which occur at high and low water, and System (D),

shown in Fig. 6, is the simplest that has so far been devised. In this system, two basins, one functioning at a high level and the other at a low level, are arranged so that the high-level basin can be filled from the sea during a rising tide, and emptied into the low-level basin through turbines which the water operates *en route*. The low-level basin is drained off into the sea on each falling tide.

The operations under this system can be followed by reference to Fig. 6, and are as follows—

Stage 1. The cycle starts with the high-level basin full, and the low-level basin part-filled. During the first stage of the cycle, water is run from the high-level basin through the turbines to the low-level basin whilst the tide is dropping.

Stage 2. When the water level in the low-level basin coincides with the tide level, its sluices and the tide sluices are opened to drain off the water contained in the low-level basin. Meanwhile, the discharge from the turbines fed by water from the high-level basin is diverted to the sea.

Stage 3. At low water, when the low-level basin is empty, the tide sluices are closed, and

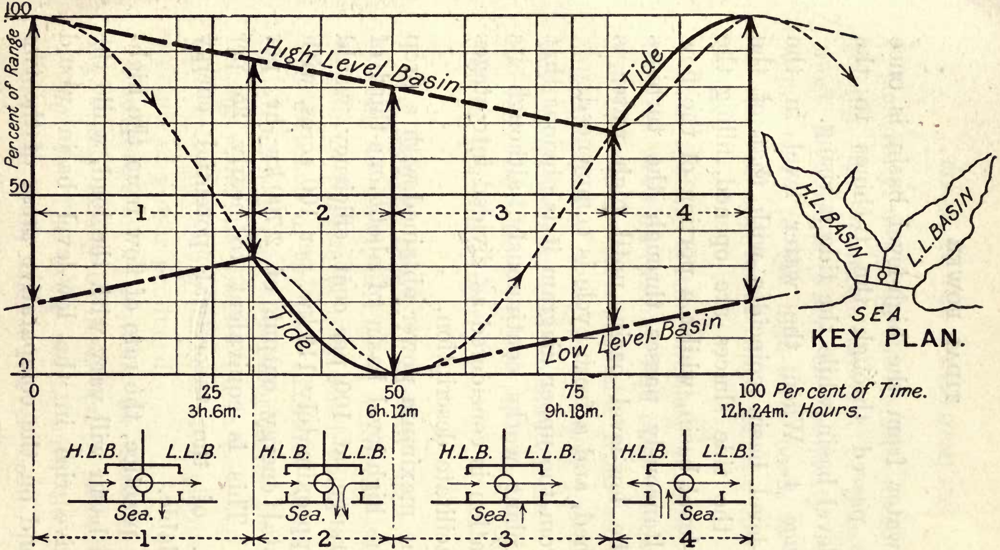

FIG. 6.—CONTINUOUS WORKING. DOUBLE BASIN
(*System D*)

the water from the high-level basin is once more passed through the turbines to the low-level basin while the tide is rising.

Stage 4. When the water level in the high-level basin coincides with that of the tide, the tide sluices are opened, filling the high-level basin, whilst a portion of the flow simultaneously passes through the turbines to the low-level basin, until high water is reached, and a fresh cycle is commenced.

From the upper diagram it is obvious that the plant works continuously, although its operation is considered as divided into stages to facilitate description.

The maximum power obtained with a drop in the high-level basin of about one-third of the range, at 100 per cent. efficiency, would be approximately 113 kw. per 100 acres, with a total energy output of 2,700 kw.-hr. per day. This is equivalent to nearly 25 per cent. of the theoretical potential energy available.

In practice, the rate of flow from the high-level basin will vary with the load, while the relative rise in the low-level basin would depend on the comparative areas of the two basins.

Generally speaking, the conditions for producing the maximum amount of power are most favourable when the capacity of the upper third of the high-level basin is equal to that of the lower third of the low-level basin.

This system is the simplest possible continuous working system, but only yields one-third of the power obtainable from an intermittent system such as (C) and practically only two-thirds of that obtained from a more efficient continuous system such as (F), which will be described later.

27. Double Basin : System (E). This system, as shown in Fig. 7, is merely a modification of System (D), in which fuller advantage is taken of the flow of water directly to and from the sea, thus shortening the time during which the basins are in use, and consequently increasing the rate of discharge and amount of power produced.

The series of operations as illustrated in Fig. 7 may briefly be described as follows—

Stage 1. The cycle starts with the high-level basin full, the low-level basin partly filled, and the tide dropping with tide sluices

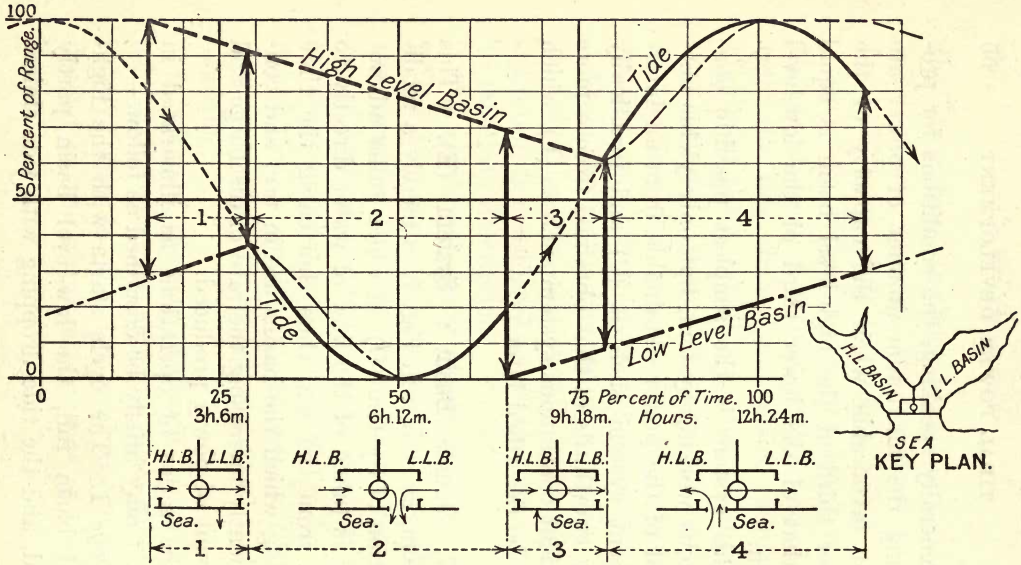

FIG. 7.—CONTINUOUS WORKING. DOUBLE BASIN
(*System E*)

closed. The turbines are operated by water discharged from the high-level basin direct to the low-level basin during this stage.

Stage 2. When the water levels in the low-level basin and the falling tide coincide, the tide sluices are opened, the flow from the tail-bay being then diverted directly to the sea, and the low-level basin being drained until low water is reached, when its sluices are closed so as to keep it empty whilst the tide rises during the remainder of the stage.

Stage 3. When the tide has risen to a height which reduces the working head to the minimum height allowable, the flow from the turbines is diverted to the low-level basin by opening its sluices and closing the sea sluices.

Stage 4. When the water levels in the high-level basin and sea coincide, the tide sluices are opened, water from the sea then filling the high-level basin until high water is reached, and simultaneously operating the plant by the passage of a portion of the flow to the low-level basin. At high water the high-level sluices are closed, retaining the water then impounded in the basin, whilst the tide drops until the minimum allowable head is again

reached, when water is once more drawn from the high-level basin, thus starting a fresh cycle of operations.

The maximum power obtainable continuously, under the conditions shown, is approximately 164 kw., giving a total output of 3,960 kw.-hr. per day. This is equivalent to 36 per cent. of the theoretical potential energy available.

This system is nearly as simple as that illustrated under System (D), and gives practically 50 per cent. more energy. It is probably the best two-basin system that can be devised.

It probably would be used where conditions were not suitable for the construction of a three-basin system, or as a first stage in a three-basin system in which the third basin would be added at a later date.

28. Treble Basin: System (F). For continuous working, the treble basin system, illustrated in Fig. 8, is suggested by the writer as a method of tidal power development likely to give the greatest possible output of power, in a comparatively simple manner, with a minimum amount of installed

plant. This system is virtually a combination of the best features of a good intermittent system such as (C) [Fig. 5], with those of an efficient continuous working system such as (E) [Fig. 7].

The arrangement of the three basins is shown on the Key Plan in Fig. 8 and on an enlarged scale in Fig. 12. Fig. 8 shows how the functions of the intermittent and continuous basin systems can be combined, so as to use one common power-house which blends their separate and distinct functions into one continuous stream of power, produced by one set of turbines, always revolving in the same direction, yet taking full toll of the greatest amount of energy which each system, within the limits of its capacity, would be capable of producing.

The essence of this system as shown in the diagrammatic plan (Fig. 9) and section (Fig. 10), is the use of a single power-house with a fore-bay on one side and a tail-bay on the other, arranged so that the greatest volume of water at the highest feasible head is supplied to the former, whilst the water discharged into the latter is drained away as rapidly as possible to ensure the lowest practicable back-water.

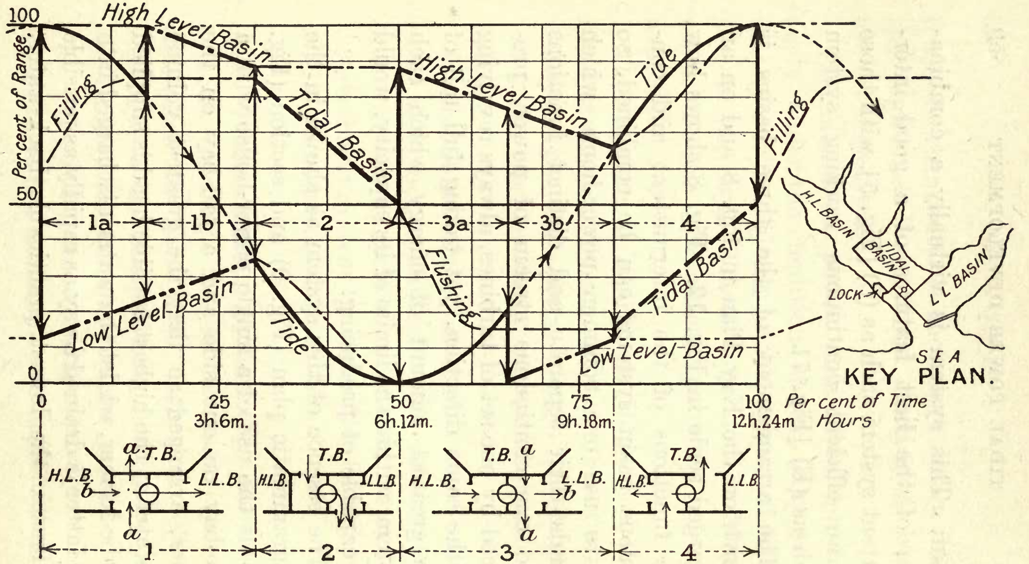

FIG. 8.—CONTINUOUS WORKING. TREBLE BASIN

(*System F*)

The cycle of operations is naturally more complicated than that in the systems previously described, but it may be grasped by reference to Fig. 8, and is as follows—

Stage 1. The cycle starts when the tide is turning at high water, with the high-level basin full, its sluices being shut, the tidal basin partly filled with its sluices open and the low-level basin nearly empty with its sluices open. During the first phase of this stage, marked 1*a*, the fore-bay is supplied from the sea, which simultaneously fills the tidal basin as rapidly as possible, its sluices being shut when the water levels coincide. The turbines take water as required from the forebay, whilst the tail-bay drains to the low-level basin. During the second phase of the stage, marked 1*b*, when the tide has dropped to the level giving the minimum permissible head, the forebay is fed from the high-level basin by opening its sluices, the tide sluices being then closed, whilst the tail-bay continues to drain into the low-level basin.

Stage 2. When the tide has dropped sufficiently to produce the requisite working head from the tidal basin, its sluices are opened to feed the fore-bay, the high-level

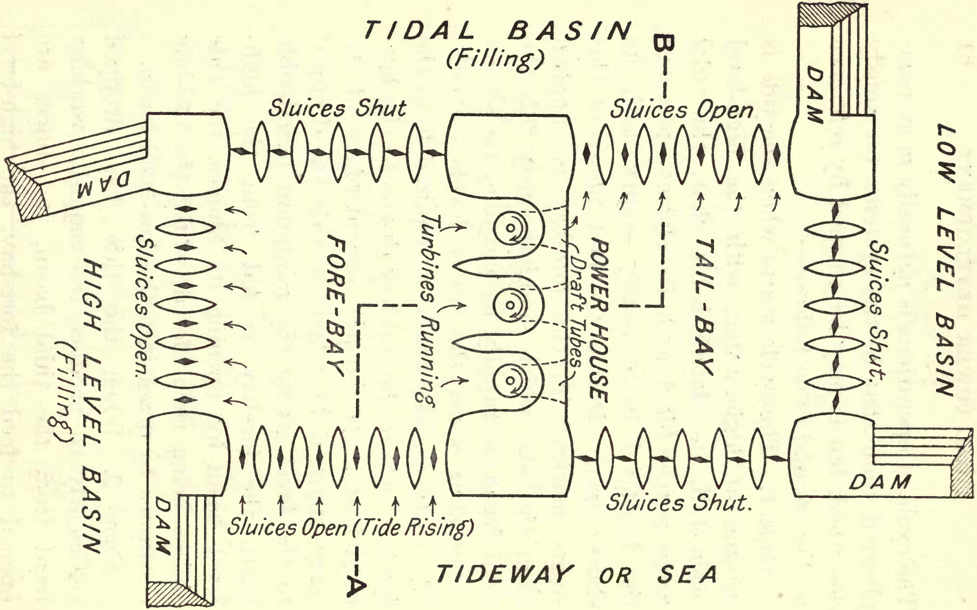

FIG. 9.—PLAN OF POWER HOUSE SHOWING CONTROL OF WATER IN FORE-BAY AND TAIL-BAY

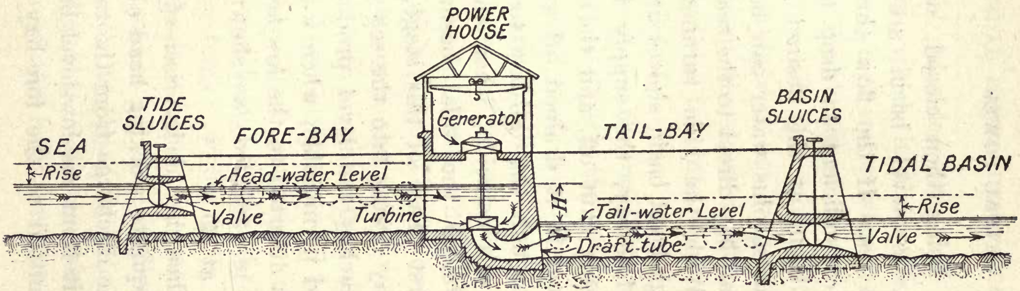

FIG. 10.—DIAGRAMMATIC SECTION OF POWER HOUSE, FORE-BAY AND TAIL-BAY ON LINE A–B (FIG. 9), SHOWING WORKING CONDITIONS DURING STAGE 4 (FIG. 8)

basin sluices being then closed, whilst the tail-bay and low-level basin are drained direct to the sea. If the flow through the turbines is not sufficient to drop the levels in the tidal basin at the desired rate, the balance of the surplus water can be drained through the tail-bay direct to the sea.

Stage 3. With the tide turning at low water, the high-level basin sluices are opened to feed the fore-bay, the supply from the tidal basin being shut off, and the remaining water contained in it drained off as rapidly as possible through the tail-bay to the sea, until their levels coincide, when the sluices are shut to keep the tidal basin empty. During the first phase of this stage, marked 3*a*, the tail-bay drains into the sea until the rising tide reaches the level producing the minimum head permissible, when water from the tail-bay is diverted to the low-level basin and the tide is excluded, as shown in the second phase at 3*b*.

Stage 4. When the tide has risen sufficiently to give the requisite working head above the tidal basin, the discharge from the tail-bay is diverted into it from the low-level basin, the sea being admitted to the fore-bay as soon

as its level coincides with that in the high-level basin, which it then fills in its continued rise to high water, when it is impounded by closing the sluices ready for a fresh cycle of operations. If the volume of water passing the turbines is not sufficient to fill the tidal basin at the desired rate, the requisite balance can be fed into it direct from the fore-bay.

Fig. 11 shows the working head and the power output during the above stages with the high-level and low-level basins, each having an area of 40 per cent., and the tidal basin an area of 20 per cent. of the total combined basin area. Under the conditions shown, with a range of 10 ft. on an aggregate area of 100 acres, the power varies from 128 to 210 kw., with a total output of 3,960 kw.-hr. per day. This output is equal to 36 per cent. of the theoretical potential energy and to nearly 50 per cent. of that of the best intermittent systems; whilst it is equal to the best two-basin continuous system, and 44 per cent. in excess of the simplest continuous system, such as (D), [Fig. 6].

From Fig. 11 it is obvious that by sacrificing a portion of the head and re-adjusting the

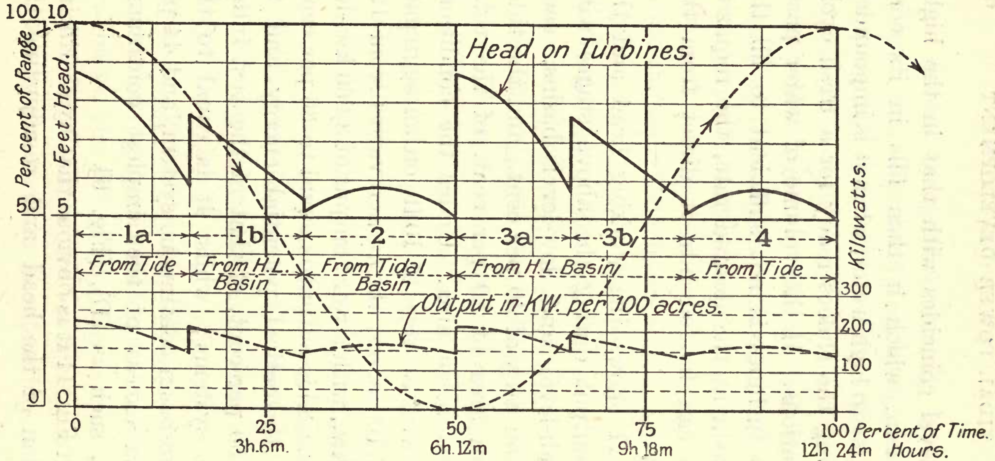

FIG. 11.—WORKING HEAD AND POWER OUTPUT FOR CONTINUOUS WORKING, TREBLE BASIN SYSTEM (F)

rate of discharge, it should be possible to confine the fluctuations in head to between, say, 55 per cent. and 75 per cent. of the range with an output of approximately 160 kw. constant power, producing a total of 3,840 kw.-hr. per day. This system should adapt itself readily to fluctuating demands for power, as the fore-bay can be fed from three sources, that is, from the high-level basin, the tidal basin, and the sea; whilst the tail-bay can be drained into three receptacles, that is, the low-level basin, tidal basin, or sea, whichever is placed in a position to work most efficiently at the time.

29. Comparison of Tidal Basin Systems. The six systems described above can readily be compared by reference to Figs. 3–8 and Table I. This table is computed for a 10-ft. range, on the supposition that the basins have vertical sides, are flat bottomed, and 100 acres in total extent. The figures are computed, from scaled heads and rates of discharge, by the slide rule, as this is considered sufficiently accurate for practical comparison of the rival systems to be made. The table shows that the average power varies

from 113 kw. under System (D) to 1,032 kw. under System (B), and that the energy output varies in the different systems from 25 per cent. to over 85 per cent. of the theoretical potential energy, which is taken as double that produced by System (A). These comparisons show that (C) is the best intermittent system, and that (D) is the simplest, whilst (E) and (F) are the most efficient continuous systems. In practice, the power and output will fall short of the figures shown in the table by the amount that the relative areas and rates of discharge actually obtained differ from the ideal conditions assumed. The actual area of the basins will obviously depend on local conditions, and should be planned to give the greatest possible output at the lowest cost. Considerable judgment will be necessary in determining the actual relative sizes of the various basins, and the allowable rates of discharge of the water flowing to and from them.

30. Constant Head Systems. Ingenious systems for operating turbines under constant head have been designed, and in some of those suggested the fixed head is produced by means of permanent structures. The chief

TABLE I.—COMPARATIVE DATA ON BASIN SYSTEMS OF TIDAL POWER DEVELOPMENT

Range 10 ft.—Combined Basin Area of each system, 100 acres

	INTERMITTENT :			CONTINUOUS :			
	Single-Basin Class.			*Double-Basin Class.*		*Treble-Basin Class.*	
						(F).	
	(A).	(B).	(C).	(D).	(E).	High-level.	Tidal.
Running time per tide, in hours	3·1	4·71	4·96	12·4	12·4	7·44	4·96
Total rise and/or fall, in feet	5·0	9·2	8·6	4·0	6·0	4·5	7·0
Rate of ditto, in feet per hr.	1·61	1·95	1·73	0·323	0·484	0·605	1·41
Supply basin area, in acres	100	100	100	50	50	40	20
Rate of discharge, in acre-feet per hr.	161	195	173	16·2	24·2	24·2	28·0
Mean working head, in ft.	5·7	5·3	5·2	7·0	6·8	7·0	5·6
Power at 100% efficiency, in kw.	918	1,032	900	113	164	169	158
Output per tide at 100% efficiency, in kw-hr.	2,840	4,870	4,460	1,400	2,040	1,260	785
Output per day at 100% efficiency, in kw.-hr.	5,500	9,400	8,630	2,710	3,960	3,960	
Output per sq. mile, in kw.-hr.	35,200	60,200	55,300	17,300	25,300	25,300	
Ratio to theoretical potential energy (%)	50	85·5	78·5	24·6	36·0	36·0	

objection to such systems lies in the fact that they are unable to meet the considerable fluctuations in range that are inevitable in all tidal power developments and that they sacrifice a large portion of the available power.

Inspection of the figures illustrating the six systems described above, shows that a constant working head could be obtained in each of them by regulating the relative water levels in the fore and tail-bays so that the difference between them remained constant.

Regulation of these levels carried to the extent that is necessary to produce a constant head, obviously causes the sacrifice of a considerable amount of the available head during part of the tidal cycle, with consequent loss of power. The sacrifice becomes serious if the fixed head is that which obtains at neap tides, which, generally speaking, only produce one-quarter of the power available at spring tides.

No constant head system has yet been devised that obviates great sacrifice of power at spring tides when the head is fixed with reference to the neap range.

For these reasons, turbines capable of

working at constant speed under considerable variations of the working head are preferable to those able to work only under a constant head.

Turbines working at a speed to give the optimum power for the head under which they are running at the time would be highly satisfactory, if the generators could be arranged to produce current at constant voltage, in spite of considerable variations in turbine speed.

This combination could probably be arranged and should prove an efficient one.

CHAPTER V

THE PREPARATION OF PROJECTS

31. Outline of Work Involved. In the preparation of projects for the development of tidal power, no hard-and-fast procedure can be laid down, as so much will depend on local conditions. It will probably be necessary to consider each case on its own merits, putting forward the project in the shape calculated to meet requirements in the simplest and cheapest manner possible. The following notes should merely be regarded as an indication of some at least of the many problems that will confront the engineer, and as bare suggestions of the manner in which he may with advantage face them.

32. Plans Required. For consideration of any projects not of a purely preliminary character, contour surveys of the proposed sites for reservoirs and tidal basins are essential as a foundation on which to work. Tacheometer surveys will, generally speaking, be found sufficiently accurate. From these

surveys, contours should be plotted at 1 ft. intervals. The reservoir site should be subdivided into basins, proportioned in size to suit the system of working to be adopted, as shown, for example, in Fig. 12.

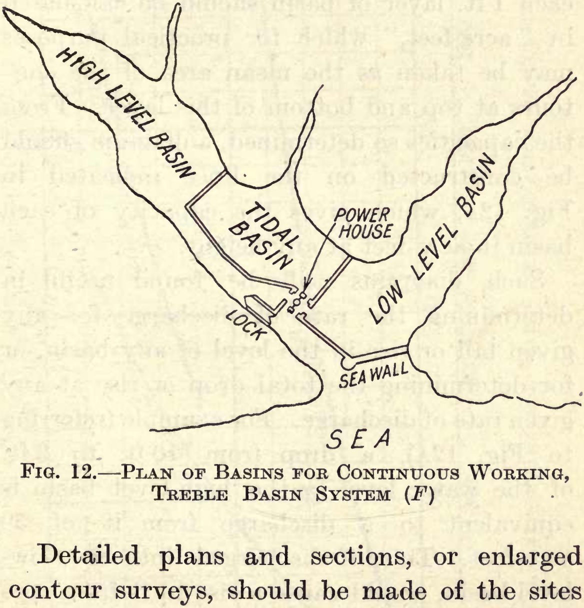

FIG. 12.—PLAN OF BASINS FOR CONTINUOUS WORKING, TREBLE BASIN SYSTEM (*F*)

Detailed plans and sections, or enlarged contour surveys, should be made of the sites of special works, such as fore-bay and tail-bay, power-house, etc. Plans showing the electrical transmission line and distribution system will also generally be required.

33. The Capacity of Tidal Basins. The area, in acres, of each 1 ft. contour of the tidal or reservoir basins should be determined. This can be done conveniently by means of a planimeter. From these areas the capacity of each 1 ft. layer of basin should be calculated in "acre-feet," which for practical purposes may be taken as the mean area of the contours at top and bottom of this layer. From the capacities so determined, a diagram should be constructed on the lines indicated in Fig. 12A, which gives the capacity of each basin in acre-feet at any height.

Such diagrams will be found useful in determining the rate of discharge for any given fall or rise in the level of any basin, or for determining the total drop or rise at any given rate of discharge. For example (referring to Fig. 12A), a drop from 10 ft. to 9 ft. of the water level in the high-level basin is equivalent to a discharge from it of 50 acre-feet. This, if discharged into the low-level basin, would cause a rise in it from zero to 1·8 ft.

This diagram would also show the approximate power output in kilowatt-hours, corresponding to any given change in level of the

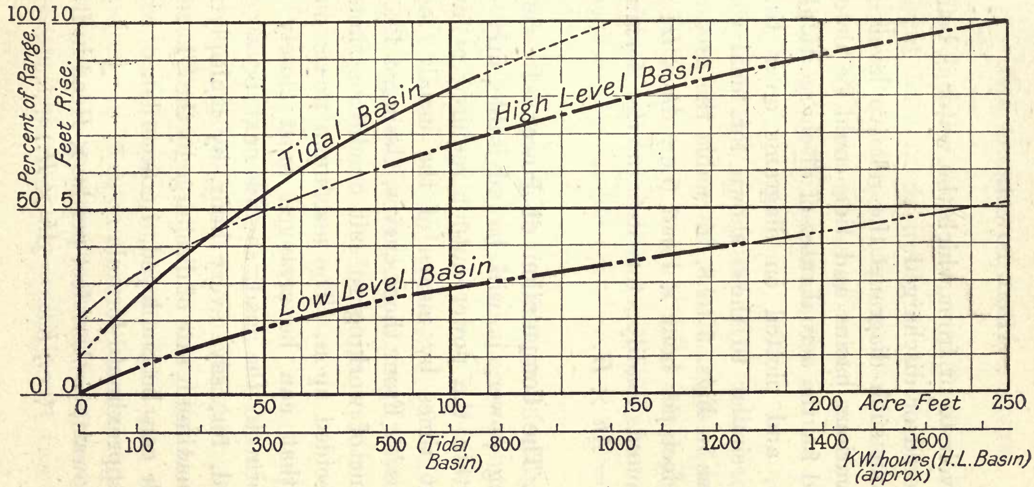

FIG. 12A.—CHART FOR RAPID DETERMINATION OF CONTENTS OF BASINS

reservoir to or from which the water is being delivered or discharged.

From such diagrams the relative levels in the various basins and tide could be determined for the actual rates of discharge taking place, and plotted on diagrams on a time basis, similar to those shown for ideal conditions in Figs. 3 to 8, to enable the product Acre-feet per hour × Head (i.e., $Ah \times H$) to be found readily, for use in the formula $Kw. = Ah \times H$.

34. The Computation of Power. In computing power, it will be advisable first to ascertain the power output required at different times by means of the usual "load curves." From these curves, the most likely system of working to suit conditions should be decided upon. The maximum power output that can be arranged most closely to conform to the load, should next be ascertained, for, say, every hour, by multiplying the maximum rate of discharge by the "head" which can be employed, in accordance with the approximate formula :

$$\text{Kilowatts} = \text{Acre-feet per hr.} \times \text{Head in ft.}$$

$$(\text{i.e., } Kw. = Ah \times H.)$$

The relative sizes of basins and rates of flow should be varied, until by trial and error methods the most efficient combination is found. Corrections for efficiency must naturally be made to ascertain the actual power available.

Considerable judgment will have to be exercised in fixing the relative sizes of basins and the rates of flow of water through the turbines to obtain the maximum amount of power at reasonable cost.

35. Design. The chief factors affecting the design of tidal power development plant and works that should not be lost sight of are: Wave action, probable silting of basins, scour at outlets, and fluctuations in range which will affect both the rate of discharge and the head under which turbines operate.

Dams. Dams or reservoir walls exposed to the direct action of the sea should be sufficiently substantial to withstand its action, and their design should be based on harbour practice. Interior walls of tidal basins might be designed in accordance with water-supply or irrigation practice. Absolute water-tightness in such retaining walls is not essential,

and, in consequence, construction in some cases may be simplified and cheapened.

Fore-bay and Tail-bay. Absolute control of the water entering and leaving the turbines is essential, to enable the requisite working head to be produced at all stages of working. It is suggested that this can conveniently be achieved by a suitable combination of fore- and tail-bays. The outline of an arrangement by which complete control of water could be effected by means of such a combination, designed by the writer, is shown in Figs. 9 and 10.

A perspective sketch of a modification of this arrangement is shown in the Frontispiece. In the three-basin system indicated in these figures the admission of water entering the fore-bay from either the sea, the high-level, or the tidal basin, will be under control. Similarly the abstraction of water draining from the tail-bay to either the tidal basin, the low-level basin, or the sea, will be capable of variation as desired. Lastly, the direct passage of water between the tidal basin and the sea will be possible, simultaneously with the flow of water through the turbines.

For single-basin systems of working, the

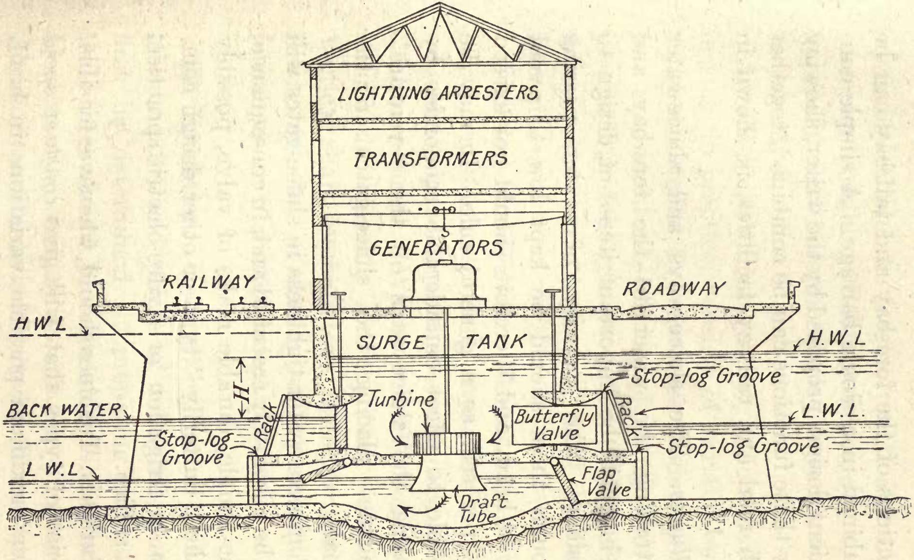

FIG. 13.—SECTION THROUGH PROPOSED BARRAGE AND POWER HOUSE FOR SINGLE BASIN SYSTEM

functions of the fore-bay and tail-bay can be combined in a single barrage. A simple convenient design, proposed by the writer, showing how these functions can be combined, together with road and railway facilities, is shown in Fig. 13.

Sluices. The sluice-ways and sluice-gates controlling the water to the fore-bay and tail-bay will be important items of design to consider. The velocity of water passing through them should be kept low to avoid loss of head, and therefore should not exceed 6 ft. per sec. as a general rule. It may be possible to effect considerable economies by forming the sluice-ways on the "venturi" principle, placing the sluice-gates in the throat.

Complete water-tightness in sluice-gates will not be absolutely essential and, in consequence, some simple, durable make of valve, possibly of the "butterfly" type or other design common in irrigation or hydro-electric practice, will suffice.

Turbines. Turbines should, whenever feasible, consist of types that will give *constant speed* under maximum possible variations in head, with the least loss of efficiency. It will be

advisable to use the largest practicable units wherever possible. Efficient automatic speed regulation in the form of relay governors will be essential.

An alternative arrangement, which may be feasible in practice, consists of variable speed turbines coupled to generators producing current at *constant voltage*. The problems involved present one of the greatest difficulties in design, as so many variable factors must be taken into account.

Electrical Installations. Generators, switchgear, transformers, and transmission lines may be designed on customary modern hydro-electric practice. Where possible, generators should be directly driven from turbines. Vertical shaft combinations, owing to the low heads usually available, will probably be found to be the most suitable type.

36. Estimates. Unit prices, based on local labour rates and prices of materials, should first be determined in preparing estimates. Quantities should be calculated to the degree of accuracy necessary to suit the purpose for which the estimate is required. Thus approximate quantities would serve for preliminary

estimates, whereas accurate quantities will be required for final projects. An estimate of *capital cost* should be prepared from the quantities calculated at the unit prices. An estimate of *annual working costs* will generally be required, and, where possible, this should be based on actual rates ruling in the locality, due provision being made for payment of interest on capital; for a sinking fund based on the "life" of the plant installed and structures erected; and for maintenance and repairs.

37. The Financial Aspect. Many factors have generally to be taken into account in considering the financial aspect of any proposed scheme. The main factors to be considered in this connection are—

(i) Existing markets.
(ii) Possible future industries, or other new markets.
(iii) Likely competitors.
(iv) Transport facilities, labour supply, and housing facilities.
(v) Climatic conditions and social amenities which frequently affect labour costs.
(vi) Other forms of power compared with that proposed.

(vii) The conservation of natural resources, which is a matter likely to take considerable prominence in the future.

(viii) Vested rights.

Estimates showing the financial position should indicate the probable return on capital involved, making due allowance for maintenance, for interest on capital, and for provision of a sinking fund based on the probable life of various sections of the installation.

Working costs, where the actual labour and material required are not known, should be based on the nearest parallel practice, or on experience gained in undertakings where the same or similar factors are likely to apply.

The *vested rights* affected, including such matters as submergence, drainage, fishing rights, navigation, roads, and railways, should be looked into, and provision should be made for the cost of their acquisition. Arrangements to secure the necessary rights should, where possible, be made by mutual consent of the various parties concerned. Where this cannot be done, legal powers, which it is hoped will be granted in the near future, should be enforced.

CHAPTER VI

FINANCIAL CONSIDERATIONS

38. Difficulties Confronting Finance. The consideration of the financial aspects of tidal power development schemes is fraught with considerable difficulty, owing to the lack of precedent. The nearest analogy to developments of this character would be low head hydro-electric installations, which are not strictly comparable, except in some of the features common to both methods of working. The issue is further complicated by lack of experience in the construction and cost of tidal basins, and of appliances for the control of the water entering and leaving them.

The problem is also rendered somewhat difficult owing to uncertainty as to the cost of any new work that will be constructed in the future, due to altered labour conditions and prices of materials. A further unknown factor exists in uncertainty as to the future value of money, which governs the markets for power, on which, in turn, industrial development depends.

Owing to these uncertain factors, it is proposed to consider the financial prospects of tidal power developments solely on the basis of the *annual savings* that will be rendered possible by their use in comparison with—

(*A*) Existing fuel-driven installations.

(*B*) New coal-driven installations.

39. Comparison (A) : Financial Aspect Based on Existing Fuel-driven Installations. The tables of Cost and Records, published as a supplement to the *Electrical Times*, furnish valuable data on the financial position of existing municipal and other electricity undertakings. The data used in this section are based on the records of thirty-six stations, with an installed plant capacity of 10,000 kw. and upwards each, averaging approximately 22,000 kw., with load factors varying from 25 per cent. to 32 per cent. An analysis of the figures given for these installations shows the following—

Capital Cost. The total capital invested in Metropolitan installations varies from £37 to £113 per kw. installed ; whilst in provincial installations it ranges from £18 to £104 per

kw. installed, with a preponderance costing between £40 and £50 per kw. installed.

The latter figure (£50) is taken as the basis of computation in this chapter, as prices are not likely to drop. The capital cost of tidal power stations will depend on local circumstances, for which no forecast can be attempted here.

Compared with steam-driven plants, the cost of tidal control works, including sluices, is likely to be less than that for boiler and condensing plants, and turbines are far less costly than steam engines for equal output ; whilst electric generators, switchgear, and transmission systems should cost the same in both cases. Hence, tidal power developments, except for the cost of the necessary basins, should be cheaper than steam.

To simplify the consideration of the problem, and to give the benefit of the doubt to steam, it is assumed that the capital cost of a tidal power station will be equal to that of a steam station for all works, excepting the actual tidal basins, or reservoirs, the cost of which is regarded as extra to that of an equivalent steam-driven installation.

Annual Working Charges. In Metropolitan

and provincial stations, the cost of coal or other fuel consumed varies from 0·3d. to 1·08d. per unit (i.e., per kw.-hr.), with an approximate average of 0·56d. per unit, the figure assumed in this comparison being 0·55d. per unit.

All other working costs, including such items as oil, water, stores, maintenance, repairs, rents, taxes, etc., vary considerably in different localities, and lumped together total from 0·17d. to 0·91d. per unit, with an approximate average of 0·38d. per unit. The figure assumed in these estimates is 0·35d. per unit.

In tidal power developments, the plant will be far simpler and easier to run than steam plants, as boilers, condensers, circulating pumps, etc., are cut out, so that the working costs will be considerably lower than in fuel-driven plants, and may drop to as low as 0·1d. per unit. To allow a margin of safety, the working costs for tidal power installations are taken as being 0·2d. per unit compared with 0·35d. per unit for fuel-driven plants.

Management expenses average 0·07d. per unit in steam stations, and the same figure is adopted as adequate for tidal stations.

Interest and Special Expenditure. The

amount set aside to meet interest and special expenditure in existing undertakings varies from 1·0 per cent. to 5·3 per cent. of the total capital invested, with a preponderance varying from 3 per cent. to $3\frac{1}{2}$ per cent.

In tidal power developments, the low rates at which money was raised for existing undertakings would not be possible, and interest is calculated at 6 per cent.

Loan Repayment and Depreciation. The amount set aside to cover loan repayment or depreciation and reserve in existing undertakings varies from 1·26 per cent. to 5·36 per cent. of the total capital, with an approximate average of $3\frac{1}{2}$ per cent.

In tidal power developments, a sinking fund should be created which will extinguish the capital cost within the life of each portion of the installation. It is assumed in this comparison that the average life of power-house generating plant, and water control appliances, etc., will be twenty years, with a sinking fund of 2·72 per cent.; whilst for permanent structures, such as sea walls, dams, etc., the life will be fifty to sixty years, necessitating a sinking fund of 0·34 per cent.

Comparative Estimates. Table II gives a

comparison of costs between a steam-driven and tidal power installation, and is based on an assumed total installed plant capacity of 20,000 kw., with a load factor of 25 per cent., giving an annual output of 43,800,000 kw.-hr. of electrical energy. This table shows the relative costs under the rival systems, giving the same price per unit, which amounts on the data assumed to 1·35d. per unit produced by each system. The table also shows that, allowing for the enormous disparity in the rate of interest assumed, namely, 3½ per cent. payable on capital expended on existing undertakings, as against 6 per cent. payable on tidal installations, £2,740,000 can be expended on the latter, compared with £1,000,000 that could be spent on an equivalent steam station.

In other words, tidal power can compete on a footing of equality with steam power as regards costs per unit produced by existing undertakings, when the capital invested in the latter amounts to £50 per kw. installed, even when the cost of tidal power stations reaches as high a figure as £137 per kw. installed.

These figures are given merely as a guide to the enormous margin in capital that would be available for expenditure on tidal power

TABLE II

Comparative Costs for Steam-driven and Tidal Power Installations

	Steam Power.			Tidal Power.		
Plant installed, in kw.	20,000			20,000		
Annual output of electrical energy at 25% load-factor, in kw.-hr.	43,800,000			43,800,000		
Capital cost (steam at £50 per kw., tidal at £137 per kw.)	£1,000,000			£2,740,000		
	£	Per cent.	Pence kw.-hr.	£	Per cent.	Pence kw.-hr.
Working Costs per annum—						
Coal consumed	100,500	40·7	0·55	—	—	—
Stores, maintenance, Rents, etc.	63,800	25·9	0·35	36,500	14·8	0·20
Management	12,800	5·2	0·07	12,800	5·2	0·07
Total working costs	177,100	71·8	0·97	49,300	20·0	0·27
Interest per annum—						
Steam £1,000,000 at 3½%	35,000	14·1	0·19	—	—	—
Tidal £2,740,000 at 6%	—	—	—	164,400	66·6	0·90
Sinking Fund per annum—						
(Interest rate: Steam 3½%, Tidal 6%):						
20-year life; £1,000,000 at 3½%	35,000	14·1	0·19	—	—	—
20-year life; £1,000,000 at 2·72%	—	—	—	27,200	11·0	0·15
50-year life; £1,740,000 at 0·34%	—	—	—	5,900	2·4	0·03
Total Annual Charges	£247,100	100%	1·35d.	£246,800	100%	1·35d.

development competing with fuel-driven plants under present-day conditions.

40. Comparison (B): Financial Aspect Based on Annual Savings. The financial aspect of tidal power may also be regarded from the point of view of the capital that could be invested in tidal installations competing with fuel-driven undertakings if the two were built contemporaneously, the basis of comparison being the saving that would be effected in the cost of fuel and working expenses.

Looked at from this standpoint, the following observations should be kept in mind—

Fuel Saved. The Coal Conservation Committee, in Appendix A of its final report dated 23rd January, 1918, stated the consumption of coal in Great Britain to be—

Average consumption before adoption of electric driving	7 lb. per h.p.-hr.*
Average consumption in present-day (1918) plants, for country taken as a whole, including central stations .	5 lb. per h.p.-hr.
Consumption in power companies' stations, with modern electrical equipment as in proposed "super-stations"	1·54 lb. per h.p.-hr.

* This figure is stated in the Report to be "almost certainly on the low side."

For a station of 20,000 kw. capacity with 25 per cent. load factor, it is assumed in the following comparison that the fuel consumption will not fall below 1·9 lb. per h.p.-hr., as this figure is not likely to be reduced in ordinary practice. This is equivalent to a consumption of 10 tons per kw. per year, which amounts to 0·55d. per kw.-hr., with coal costing 40s. per ton. This expenditure is saved by the use of tidal power.

The Cost of Coal. The Board of Trade Coal Mines Department Statistical Summary for the three months ended 31st March, 1920, gives the following statistics on coal raised in Great Britain—

Quantity raised . . .	62,057,000 tons
Total costs	29s. 6·72d. per ton
Commercial disposals . .	34s. 6·91d. per ton

Statistics published by the Minister of Transport for February, 1920, show that coal haulage amounted to approximately 730,000,000 ton-miles, with an average haul of approximately 45 ml., and that the gross receipts varied from 1·286d. to 1·626d. per ton-mile. Assuming an average of 1·5d. per ton-mile, the cost of transport on an average haul of

45 ml. equals 5s. 7½d. per ton. It is assumed, therefore, in this comparison that the price of coal delivered at a generating station that would be capable of competing with a tidal station would not be less than a total of 40s. per ton.

For a station with 20,000 kw. installed, it is assumed that the working costs, as indicated in §39 above, will be 0·35d. per kw.-hr. for a steam station as against 0·20d. per kw.-hr. for a tidal power station. The saving, therefore, in the latter is 0·15d. per kw.-hr., giving a combined total saving per unit amounting to—

Coal unconsumed . . .	0·55d. per kw.-hr.
Reduction in working costs .	0·15d. ,,
Total saving in favour of tidal power . . .	0·70d. per kw.-hr.

This saving on 43,800,000 kw.-hr. equals £128,000 per year, which could be devoted to the payment of interest and sinking fund charges on a capital expenditure of £2,000,000 *additional* to the sum for which an equivalent steam station could be erected.

As in tidal power stations all works, except dams, should cost less than in steam stations,

this annual saving could be devoted entirely to defraying the cost of reservoirs and basins. Assuming a life of sixty years, the sinking fund on such works would be 0·34 per cent. on the additional capital expended on their construction. The annual saving could then be devoted to the payment of the following charges—

	£
Interest on cost of dams, etc.: £2,000,000 at 6%	120,000
Sinking fund on capital at 0·34% . .	6,800
Balance in hand	1,200
Total annual charges . . .	£128,000

This means that the enormous margin of £100 *per kw. installed* could be expended on a tidal power station *over and above* the expenditure per kw. on works costing the same as those of a steam station giving the same total cost per kw.-hr.

The *Electrical News* of Toronto, dated 15th February, 1920, gives the cost of dams for a 90,000 gross-h.p. proposed tidal installation at Hopewell at $4,000,000, i.e., £15 per kw. installed (assuming $4·00 = £1). This sum is equal to only 15 per cent. of the additional cost that could be incurred on the basis

assumed above, and indicates that tidal power installations may, under favourable conditions, be constructed at a capital expenditure well within the margin available in competition with steam.

41. Capital Involved. The capital that can profitably be invested in tidal power developments will depend entirely on the financial prospects opened up by prospective markets. These again will be affected by the cost per unit of power produced, which will be largely influenced by the amount of capital involved in the construction of the necessary works.

Unfortunately, lack of experience makes it difficult to give any indication of the cost of such works in England. At Hopewell, in New Brunswick, there is at present under consideration the construction of a tidal power development with an initial installation of 90,000 h.p. gross, capable of being increased ultimately to an installation of 200,000 h.p. gross.*

The *Electrical News* of Toronto, dated

* See also *Electrical Times*, 11th December, 1919.

15th February, 1920, gives the following estimate of cost for the works proposed—

	Dollars.
Dams	4,000,000
Lock (W. dam)	100,000
Sluices, gates	300,000
Power-house	200,000
Turbines and generators at $40 per gross h.p.	3,600,000
Transmission lines	1,200,000
Preliminary dredging, dam trench, etc..	100,000
Promotion, engineering fees, etc. . .	500,000
Auxiliary plant to supply head deficiency at subnormal neap tides . . .	1,000,000
Initial development to produce 90,000 gross h.p.	
Total . . .	$11,000,000
Cost per h.p. developed . . .	$ 122·50
Cost of full development to produce 200,000 gross h.p. . . . . .Total	16,000,000
Cost per h.p. developed . . .	80·00

For the initial development, the estimated cost is $122·50 per h.p., i.e., £41 per kw. installed (assuming $4·00 = £1).

In an article on "Water Power in Canada," in the *Electrical Times*, 13th May, 1920, there are quoted figures published by the Bureau of Statistics of the Department of Trade and Commerce, co-operating with the Water Board of the Ministry of the Interior of Canada, which show that the capital invested per h.p. installed, including transmission and distribution system, is equal to $210 per h.p. on a total capacity of 2,418,000 h.p.

Of this power, hydro-electric installations, with a total capacity of 745,797 h.p., exclusive of distributing systems but including all costs at the power site, amounted on pre-war figures to $50,740,468. This is equivalent to an average of $69·11 per installed h.p. or, at $4·00 = £1, an average of £23·25 per kw. installed.

In Tasmania, for a power station with a capacity of 57,200 electrical h.p.,* the capital cost up to power station terminals is given as £26 per electrical h.p., excluding the transmission line and distribution system.

The Power Resources Committee of the Board of Trade, in 1919, stated that for nine hydro-electric power schemes in Scotland, the cost (at 50 per cent. above pre-war figures), it was estimated, would average £38·5 per effective electrical h.p. developed. This Committee further stated that hydro-electric power could compete on a footing of equality with the very best steam stations, provided the cost did not exceed £60 per effective electrical h.p. Owing to the advance in cost of labour and materials, these prices at the present time would need to be considerably increased. In

* See *Electrical Times*, 10th June, 1920.

the building trade, for example, present prices are 3 to $3\frac{1}{2}$ times the pre-war prices.

The examples quoted above lead one to hope that, under favourable circumstances, the cost of tidal power installations may fall considerably below the limiting expenditure, which would still permit them to compete on a footing of equality with the best steam or other fuel-driven stations.

One of the chief factors likely to affect the amount of capital that can be expended on tidal power installations will be *the magnitude of the market for electrical energy.* From experience gained in operating hydro-electric power undertakings, it may be assumed that, given favourable conditions, such markets can be of great magnitude.

For example, Mr. Leo G. Dennis, the hydro-electric engineer of the Canadian Commission of Conservation, gives * the following examples of the size of hydro-electric installations—

> The power developed on the Canadian side of Niagara is 211,300 h.p., and this supplies 150 distribution systems, covering an area of 210 × 85 ml.
>
> In Quebec, the Shawinigan Water and

* In an article quoted in *The Engineer*, 9th April, 1920.

Power Co.'s plants, a feed system which has a total of 270,000 h.p. installed, and supplies 85 distribution systems within a triangle of 140×75 ml.

These figures show that with modern plants the use of electric power, produced by turbines and transmitted over long distances, can assume very large proportions (*see also* § 48). With electrical transmission, it is possible to produce tidal power at localities situated considerable distances from the markets in which the energy will be used, and it is probable that the financial prospects may in many localities prove sufficiently favourable to tempt investors to subscribe the requisite capital.

42. Indirect Benefits Arising from the Use of Tidal Power. One of the greatest benefits conferred by the use of tidal power would be the conservation of coal, which is one of the world's most important resources. The Water Power Resources Committee of the Board of Trade, in its report dated June, 1918, states that, in 1917–18, steam stations in Great Britain (not including private power plants) generated 4,628 million Board of Trade units and consumed 7,160,000 tons of coal.

The Coal Conservation Committee, in its final report, dated 23rd January, 1918, states that in the United Kingdom the annual output of coal is 287,430,473 tons, of which 189,092,369 tons is reserved for home consumption, and that of this coal 80,000,000 tons per annum is used in the production of motive power in the United Kingdom. This Committee also states that if power were developed on comprehensive lines and advantage taken of the most modern engineering practice, the saving in the consumption of coal would amount to 55,000,000 tons per annum on the above total. This enormous saving is said to be possible if existing plants, which are now exhausting needlessly the nation's wealth, were replaced by more efficient plants.

Such figures show the national importance of any means that can be devised for saving coal, which is one of the most important assets of the country, and is now being squandered lavishly by a spendthrift, short-sighted community. There is no doubt that utilization of the tides will some day be a powerful agent for effecting important savings in this essential, consumable commodity.

Further benefits that would be conveyed by the development of cheap tidal power would be the creation of many new industries which would be opened up by the establishment of electro-chemical processes, or of electrical furnaces capable of producing such materials as aluminium, fertilizers, and explosives.

CHAPTER VII

RESEARCH

43. Ample Scope for Research Work. Splendid prospects open out for research in the various problems affecting tidal power development, and there is ample scope for the display of originality, as the field is practically untrodden. The problems involved are of considerable complexity, and will provide generous room for ingenuity in their solution, especially as the use of tidal power will ultimately extend over a large portion of the earth. Much of the research will be of great interest, and in course of time will prove of great service to the civilized world.

44. The Investigation of Projects. The investigation of promising projects for tidal power development is a matter deserving of immediate attention, as time must inevitably elapse before the necessary data required for formulating projects can be collected and put into shape. An early start should be made in taking observations and collecting

data that will be useful, and in some instances essential, in formulating definite schemes for the utilization of tidal power, particularly on such subjects as currents, the deposition of silt, the action of storms, and local peculiarities likely to affect the construction of works. Tide-gauge records should be taken where possible, and likely markets should be investigated, as well as the possibilities of developing new industries.

Where the tide range and general conditions for power development are favourable, promising sites should be surveyed roughly, and preliminary projects prepared with estimates giving the approximate capital outlay necessary and the annual income that may be expected. If these estimates show the financial position to be favourable, then the preparation of detailed projects should be undertaken, on which capital can be raised for the execution of the necessary works.

A commencement in the investigation of suitable sites would obviously be best undertaken in localities where the range of tide is high, and where likely markets for the consumption of power are fairly close at hand

or where the costs of transmission will not be excessive.

It is an open question whether work of this character should be undertaken by the Government or by private individuals or corporations. The latter course would probably be greatly preferable, provided that laws were so framed as to enable private companies or local authorities to acquire the necessary rights without undue cost and trouble. The acquisition of such rights will probably be dealt with best by conferring suitable powers on properly-constituted authorities.

The collection of data and carrying out of observations of a general character are functions that the Government should rightly assume, while the preparation of specific projects and the execution of actual works might be left to private enterprise.

45. Improvements in Plant Design. There is ample room for research having for its object the evolution of plant which will enable the greatest benefit to be secured from the use of the tides, and which will solve the difficulties due to the large fluctuations in their range. Meantime, attempts

should be made to design turbines which will give a higher efficiency under far wider variations of head than is possible under existing practice, as it is desirable considerably to improve performance in this respect, if anything like reasonably full use of the tides is to be achieved. Some progress in this respect may be possible by improvements in the design of gates, guides, and runners, or combinations of runners on the same shaft which will give a constant speed under considerable fluctuations in both the volume and head of water used.

Improvements in electrical generators capable of keeping constant voltage with varying speeds of the turbine should also be possible, and this subject well merits investigation and experiments with units of the largest size likely to be installed in tidal power stations.

Methods for effecting the automatic control of the water feeding the turbines are also worthy of study, and are likely to bear an important part in actual developments, especially as human labour is becoming daily more costly, and is not always reliable. Automatic control might be achieved by devices which, under the *difference* of head in the

various basins, actuate relays controlling the motors which operate the sluice-gates.

46. Tide Storage Problems. Investigation of the problem of storing water to provide a reserve for making up the deficiency of power which occurs during neap tides is highly desirable. This investigation should be extended to cover the best means of utilizing the surplus power which is available during spring tides for pumping into storage reservoirs which can be drawn on during periods when there is a shortage of power. These problems are by no means simple, and are deserving of close study as regards the suitable arrangement of basins, reservoirs, and other works, and their cost. Endeavours should be made to devise means for minimizing the losses that are inevitable in the conversion of power during the various stages of its use in this way.

Local conditions at specific sites should be studied with a view to determining the best combination and relative sizes of basins, and storage reservoirs required to give the greatest efficiency and to make the best possible use of the potential power available.

In selecting storage reservoir sites the geological structure of the land affected by the works and the stored water should receive careful study.

47. Electrical Storage Problems. Some simple, cheap method of electrical storage on a large scale would be invaluable in tidal power developments, as it would go far towards solving the difficulties due to the fluctuations in range between spring and neap tides; also it would bridge over the "dead" periods which occur in the running of plant in intermittent systems, which give the greatest proportion of the power available. (*See* Table I.)

It is obvious that really efficient and cheap electrical storage would largely reduce the cost of tidal power, as the construction of elaborate basin systems would be obviated if power could be stored electrically, as and when generated, by the simplest possible means such as are provided by the intermittent systems of working, which have been described.

Electrical storage batteries built on the lines customary in existing practice are too elaborate and costly for use on the large scale that would

be necessary in tidal power development. In any case, existing batteries are not suitable for equalizing the great difference between the power output at spring and neap tides.

48. Electrical Distribution Systems. The question of feeding current produced by tidal power into a common distribution system, which is also supplied from other sources such as steam-driven or hydro-electric installations, is a matter well worthy of investigation. If tidal power can be fed into a distribution system directly it is produced by the tides, only the shortage (compared with the demand) being made up from auxiliary steam or hydro-electric stations, it may be possible to deliver electrical energy to the consumer at a price per kw.-hr. considerably lower than that of energy produced by the usual methods. Where conditions are favourable for such combinations, very considerable savings in coal consumption should also result.

The question of feeding one common distribution system from several tidal power stations working at different tidal intervals, that is, from stations having a different

"establishment," may also prove a useful and profitable field for investigation. In a country like England, with densely-populated industrial areas well within the limits of distance over which power can be transmitted electrically, and with a coast on which the range of tides is high, the prospects of such combined power schemes appear to be distinctly promising.

The possibilities of the arrangement suggested may be illustrated by reference to the United States.

Interconnection of electricity supply systems has been carried out on an exceptionally large scale in California, where the networks of some fifteen power companies cover a strip of country 150 to 200 miles in breadth, and about 800 miles long. The Montana Power Company operates thirteen interconnected hydro-electric plants without any steam reserve, and serves such loads as mines, smelters, refineries, and railways, for all of which continuity of service is very important. Even coal mines are supplied with power from this system. The transmission network has been laid out to provide for almost any industries which may be developed, and to

permit of ready connection with new hydro-electric plants which may be constructed. According to the *Electrical World*, 8th May, 1920 (which gives an extremely good description of American hydro-electric power developments and interconnected transmission schemes), the total rating of the Montana Power Co.'s thirteen hydro-electric plants is 212,340 kw. The connected load is about 316,000 h.p., and about 800,000,000 kw.-hr. per annum are distributed to 44,500 consumers (*excluding* large mines, smelters, refiners, and railways) by 1,922 miles of transmission line in a district 260 × 300 miles. Supply is given at the lowest average price in the United States.

49. Electro-Chemical Uses of Tidal Power. A big field for the use of tidal power will be opened out if electro-chemical industries can be established capable of taking tidal power as and when produced, especially if this can be carried to the extent of taking power from stations working under intermittent systems. This would enable the greatest amount of power to be extracted from the tides in the simplest possible manner, and should result in tidal power being produced cheaply enough

to make possible large expansion in such industries.

The difficulties to be encountered in any such methods of working are naturally considerable, and may prove to be insuperable in practice, but the subject is of sufficient importance to merit careful investigation.

50. Conclusion. Doubtless many fields for research other than those sketched above will be opened up from time to time if tidal power plants are actually started, as it is hoped that they will be at no distant date. Any fresh knowledge that can be thrown on the subject is bound to be of very great benefit to the civilized communities of the world to whom the use of power in various forms has become a necessity of life, since it has taken the place of slave labour.

It is hoped that the information and suggestions given in this book will help to stimulate interest in a subject that is probably destined soon to play an important part in the future of industry. After a great deal of spade-work has been done in this field, it may be advantageous to deal more fully with the subject than can usefully be done at present.

Meantime, contemplation of the problem of harnessing the tides prompts the sigh that escaped from Cecil Rhodes at the end of his strenuous and eventful life: "So little done, so much to do."

INDEX

ACRE-FOOT, 14, 16, 74
—— -hour, 15, 17
Admiralty tide tables, 10, 13
Annual costs, 82, 83, 86, 90
Apogee, 8
Automatic control of plant, 105

BAROMETRIC pressure, 11
Barrages, 32–34, 79, 80
Basins, capacity of, 74
Basin systems, 37 *et seq.*
—— ——, comparison of, 67

CANADIAN water-power, 29, 96
Capacity of basins, 74, 77
Capital costs, 82, 85, 89, 90, 93, 96
—— involved, 95
Civil engineering aspects, 33
Coal conservation, 99
—— costs, 92
Comparison between cost of tidal and fuel power plant, 85 *et seq.*, 90, 93
—— of basin systems, 67
Compressed air systems, 36
Constant head systems, 68
—— systems, 27, 32, 38
Contemporary tides, 12
Continuous working—
Compared with intermittent, 67
Double basin, System D, 51
—— ——, System E, 55
Treble basin, System F, 58, 73
Control of water, 62, 78, 105
Costs, 82, 83, 85 *et seq.*, 90, 92, 96
Co-tidal lines, 12
Cusec, 15, 16

DAMS, 77, 94
Dee, 32
Depreciation, 88
Design, factors influencing, 77, 98
Development prospects, 28, 72, 102
Developments, difficulties in, 25, 84
—— under consideration, 24, 95 *et seq.*
Difficulties to be encountered, 25, 84
Distribution, electrical, 98, 108, 109
—— system, 27

EARTH, rotation of, 1
Ebb, 4
Efficiency, corrections for, 18, 25, 77
Electrical aspects, 33, 105
—— distribution, 98, 108, 109
—— installations, 81
—— storage, 107
Electro-chemical uses, 27, 31, 101, 110
Equinoxes, 8
Establishment of localities, 11, 109
Estimates, 81, 83, 90, 93, 96
Examples, 18, 23, 69, 74, 90, 93, 96, 97, 109

FINANCIAL aspect, 82, 84 *et seq.*, 90, 93, 95
Floats, 36
Flow of tide, 4
——, rate of, 15
Fore-bay, 62, 78
Formulae, 16
——, examples of use, 18
Fuel consumption, steam stations, 91
Fundy, Bay of, 10, 23

GENERATORS, choice of, 35, 81, 105

HEAD, constant, 68
—— limitations, 26, 68
——, working, 66
Height of tide, 12
High water, 4, 6
Hopewell, 24, 95
Horse-power, 15, 17
Hydraulic aspects, 33, 105
Hydro-electric installations, 97 *et seq.*, 109

INDUSTRIES, development of new, 27, 31, 98, 101, 110
Interconnection of power lines, 109
Interest, 87, 90
Intermittent systems, 26, 31, 38
Intermittent working—
Compared with continuous, 67
Single basin, System A, 40
—— ——, —— B, 43
—— ——, —— C, 47

KILOWATT, 15, 17

LOAD curves, use of, 76
Loan repayment, 88
Low water, 2, 4, 6, 7

MECHANICAL aspects, 33
Moon, quarters of, 3
——, revolution of, 2

NATURAL facilities, 21, 37, 103
Neap tides, 5, 7, 8, 13, 27, 70

PADDLE-WHEELS, 36
Perigee, 8
Plans required, 72
Plant, design of, 77, 98
Power, computation of, 76
——, magnitude of field for, 28
——, potential, practicable, 21, 23
——, theoretical, of tides, 20
——, used in factories, etc., 29
——, variation with range, 22
Power-house, plan, 62
—— ——, section, 63
Projects, preparation of, 72, 102
Proprietary rights, 26, 83
Prospects, 28, 72, 102

QUARTERS of moon, 3

RANGE, influence on power, 22
——, mean English, 10, 25
—— of tides, 7–11, 13, 25
Research, scope for, 102
Reservoirs and spring-tide storage, 28
Reservoir systems, 37 *et seq.*
Rise of tide, 12

ST. MALO, 10, 23
Scottish costs, 97
Seine, 24
Severn, 10, 23, 32, 34
Sinking fund, 88, 90
Sites, 21, 37, 72, 103
Sluices, 80
Solstices, 8
Spring tides, 2, 5, 8, 13, 27, 70
Storage, 28, 35, 106, 107
Surveying sites, 72
Symbols for units, 15 *et seq.*
Systems of tidal power development, 26, 31, 36 *et seq.*

TAIL-BAY, 62, 78
Tasmanian costs, 97
Tidal power, fields for use of, 26, 98, 101
—— —— problem (Official Report), 31 *et seq.*
Tide-day, 7
Tides, formation of, 1
——, height, 12
——, neap, 5, 7, 8, 13, 27, 70
——, range of, 7–11, 13, 25
——, rise, 12
——, spring, 2, 5, 8, 13, 27, 70
—— theoretical power 20
Tide tables 10, 13, 103

Turbines, constant head, 71
——, head limitations, 26, 35
——, low-head types, 35
——, size of units, 35, 81
——, variable head, 71, 80,105

UNITS of measurement, 14 *et seq.*
——, symbols for, 15 *et seq.*

VENTURI sluices, 80
Vested interests, 26, 83

WATER power in Canada, 29, 96
—— —— Resources Committee's Report, 31 *et seq.*
Wind, effect of, 11
Working costs, 83, 86, 90, 93

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